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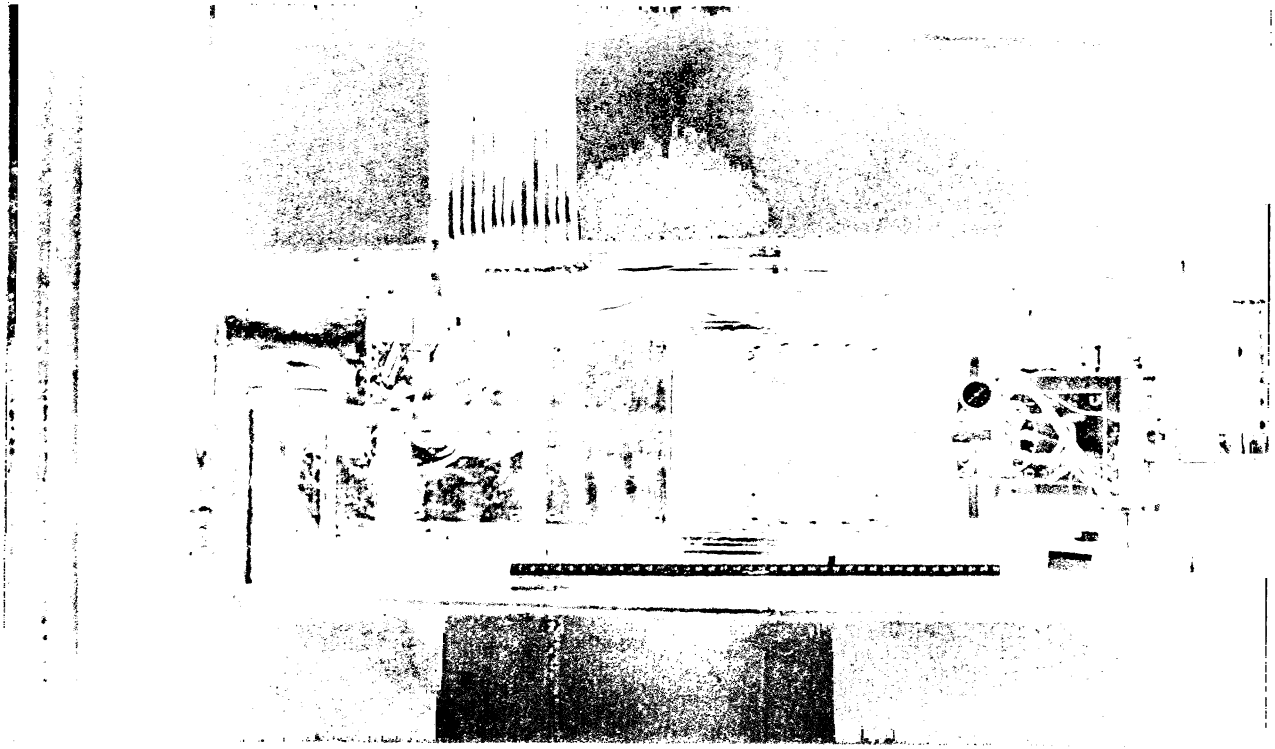

THE CENTRAL STRUCTURE OF THE 220 TON LAWRENCE CYCLOTRON AT THE UNIVERSITY OF CALIFORNIA

The Evolution of Modern Physics

By

CARL TRUEBLOOD CHASE, PH.D.

The Franklin Institute of the State of Pennsylvania

FORMERLY *Associate Professor of Physics, New York University*

Staff Member, M.I.T. Radar School

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TO

M. A. C

PREFACE

IT HAS BEEN SAID that a study of history is essential to a full understanding of the world we live in. This statement is especially true in the realm of science, which underlies and determines many aspects of the modern world.

In this book an attempt has been made to show in broad perspective the triumphal march of physical discovery from the dawn of science to the present. Special emphasis has been placed upon those researches which have made history and are now regarded as scientific landmarks.

Many discoveries of doubtful or temporary interest have not been mentioned, and some of great interest but not lying along the main line of progress have been omitted. Theoretical investigations bearing on important experiments as well as theories which have arisen from such experiments are discussed briefly in order to show why the experiments are of interest or of importance in the historical line of development. Purely mathematical investigations have not been included, nor has astronomy a place in this volume except in the few instances where it is inseparable from physics. Philosophical and theological implications must also in large part be left for other volumes.

It is hoped that, by thus limiting the scope of the book, the more important steps in the development of physics to its present eminence may be treated with the adequacy which they deserve, and that at the same time the general trend of historical development, with the dependence of each stage on those preceding it, may not be lost.

C. T. C.

Philadelphia, Pennsylvania
October, 1946

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Chapter 1

ENERGY AND ATOMS

THE IMPACT of the atomic bomb on modern civilization has no counterpart in the entire history of the human race. At no time prior to this sudden release of atomic energy has an agency so destructive, so terrifying, and for most persons so unsuspected, ever been available. Science and technology, after a long development characterized by increasing importance in the intimate and public life of everyone, everywhere, have in one rapid stride reached a point where the destruction of civilization may wait on the whim of some few persons in a nation determined on aggression.

While scientists and engineers are perfecting the processes by which atomic energy is released for military and peaceful purposes, the rest of us may wonder how it all came about, and where we go from here.

The atomic theory of Democritus and the modern atomic theories indicating the possibility of the large scale release of atomic energy are separated by centuries and by a long line of discovery and development. Each discovery has followed logically and in some cases irresistibly from others; in many cases such advances occurred as soon as they became possible, in others as soon as a definite human need for them appeared. Science and technology have at all times been partners. The discoveries of the scientists, resulting generally from an unselfish pursuit of the unknown and a desire to know more about this world we live in, have been put to use by the engi-

neer to build and heat and light our homes, to move us from place to place, to entertain us—and to destroy us. One wonders why one of the most altruistic efforts of mankind should turn out in practice to be the most destructive of human values.

Modern civilization is complex, and the political organization of the modern state is in most cases quite involved. It is possible to gain a superficial knowledge of such an organism by studying it in detail, but no complete understanding, no thorough comprehension of the way we are governed is possible without some knowledge of the history of government and political thought. When one knows something of what civilization has gone through in evolving modern democracy, it becomes possible to appreciate to a greater extent the advantages as well as the possible disadvantages of the democratic form of government. The historical study is especially important for those citizens who take an active interest in their government and strive continually to make it more effective.

In the same way, a study of the logical and organic growth which is science has many rewards for the thoughtful person, whether he be a scientist, an engineer, or a citizen bewildered by atomic energy. Such a study will convince him, for example, that as long as civilization persists, and we are not so sure as we once were how long this will be, scientific discoveries will be made and nothing will stop them; that these discoveries will be applied to the affairs of man, and that nothing can stop the process. Unfortunately, history will not show clearly that these discoveries will be devoted entirely, or even largely, to peaceful uses. But what is done with them (and something will be done, history shows this clearly) depends on what the people desire and determine shall be done. And the people will be in a better position to decide what shall be done, and will be able to work more decisively toward the desired end if they are familiar not only with the history of thought, civilization, and government, but also with the his-

tory of the science which now is in a position to produce either an ideal world for civilized life or a holocaust in which civilization may perish.

The modern scientist is a specialist, very different from the natural scientist of a century or two ago, or the philosopher of early days. Physics is one of the specialties of modern science. Atomic energy has been released by the combined efforts of physicists, chemists, mathematicians, and many sorts of engineers, but the indications that the energy was there and might be released if suitably manipulated, were obtained through the science of physics. Atomic energy, at least in its scientific aspects, belongs naturally to the physicist, for physics itself is principally concerned with energy—what it is, how it is liberated, and (especially now) how it can be controlled.

The principle of the conservation of energy, so widely recognized today, was for over a century confined to the realm of mechanical energy: kinetic energy of motion, and potential energy of position or condition.

The concept of the conservation of mechanical energy dates from the time of Leibnitz and Newton, during the latter part of the seventeenth century. The inclusion of heat as a form of energy occurred during the middle of the nineteenth century, at which time the law of the conservation of energy, as accepted at present, was formulated.

As will be noted later, early experiments in the field of mechanics, especially those of Galileo and Archimedes, prepared the way for the statement by Newton of the famous three laws of motion. At about the same time ideas concerning momentum, *work* as physically defined, potential and kinetic energy, and relations between these quantities, were gaining in clarity.

The French philosopher Descartes (1596-1650) recognized that under certain conditions momentum is conserved. Leibnitz (1646-1716) was willing to go further, and became convinced of the conservation of what was called "vis viva," the

quantity mv^2, which differs from kinetic energy by a constant factor of 2. It is generally recognized that Leibnitz had a definite idea of the conservation of mechanical energy, and that Newton (1642-1727) certainly did. Potential energy may be changed into kinetic energy and vice versa.

In a single mechanical system not acted on by external forces, the sum of potential and kinetic energy was supposed to remain constant, provided none was "lost." At present we would say, provided none is converted into other forms of energy such as heat. The earlier proviso was expressed somewhat as follows: "Forces acting in a system may be elastic forces or they may be frictional forces; in the former case mechanical energy is conserved, while in the latter it is not." We read, therefore, of conservative and nonconservative systems. A conservative system is one in which all forces are such that no mechanical energy will be lost; such forces are called conservative forces. Frictional forces, on the other hand, were called nonconservative forces; if such forces were present, the principle of conservation was considered not to apply.

As has been pointed out by other writers, the discovery that heat is a form of energy has one aspect of great scientific importance. Heat energy is easy to measure, more so than some forms of mechanical energy if a direct measurement is desired. Consequently the conservation law may more conveniently be put to experimental test.

As recently as a very few decades ago, textbooks of physics and chemistry gave equal importance to the laws of the conservation of matter and the conservation of energy. In recent years it has become apparent that one of these laws is completely embraced by the other.

Without demanding experimental proof, the early Greek atomists, principally Democritus, believed in the atomic constitution of matter. Later, when the atomic theory became more scientific and the atom a definite concept having properties which were available to experimental study, the idea of

the conservation of matter came for a time to be considered as firmly established: Matter is indestructible; matter may be changed from one form to another, as water to ice or water to gaseous hydrogen and oxygen, but matter can never be created or destroyed. Moreover, no two solid bodies can occupy the same place at the same time.

The scientific atomic theory dates from the time of Dalton (1766-1844), Avogadro (1776-1856), and their followers, and has been most useful in the development of modern chemistry as well as physics up to the first decade of the present century, at which time drastic revisions became necessary.

The principle of the conservation of matter began to weaken with the discovery by Becquerel, in 1896, of radioactivity. When it was found that the particles emitted by radioactive atoms could penetrate sheets of metal and other substances, it was no longer possible to believe that two bodies could not occupy the same place at the same time. And now that it is possible to observe the destruction of electrons with the emission of radiant energy, the creation of electron pairs by the absorption of radiant energy, and the violent alteration of some of the mass of the uranium atom into energy, it is evident that the principle of the conservation of matter must be discarded.

Today, matter is most accurately regarded as a form of energy. The relation between matter and energy or, more accurately, the energy equivalent of matter, is given by Einstein's famous formula: $E = mc^2$. E is the amount of energy which is liberated in the annihilation of a mass m of matter, and c is the velocity of light in free space (or the ratio of the electrostatic and electromagnetic units, about which more will be said). We may now speak correctly of grams of heat, or pounds of light.

Thus we are left today with the great principle of the conservation of energy, which not only is more accurately verified than ever before, but which has absorbed the principle, held valid for many years, of the conservation of matter. Matter

and energy are interchangeable, which is to say that they are essentially the same thing. Matter may be destroyed, but energy can be neither created nor destroyed; it can only be changed into other forms.

With our present knowledge of the atomic constitution of matter and of the structure of the atom, it has become necessary to distinguish between large-scale processes and small-scale processes. The words macroscopic and microscopic are used respectively to describe these processes. If a volume of heated gas is allowed to cool, or expand, the process is a macroscopic one, if we consider the gas as a whole. Likewise the evaporation of water from a drinking glass is a macroscopic process. The prediction of the science of thermodynamics, which is concerned with such processes, would be that the water would never return to the glass unless someone collected the molecules, in which case work would have to be done on them.

One may however consider each molecule and study its position and velocity. In this way we are dealing with a host of microscopic processes. Each molecular velocity may be examined, and one may compute the probability that in some manner, perhaps by their impacts with each other and with other objects, enough molecules will suffer such changes in velocity that they will eventually return and partly refill the glass. The probability of this occurrence is of course very small. Nevertheless, the process has a slight possibility when looked at in this way, though it has no possibility whatever when studied through the laws of thermodynamics.

The study of complex systems in this way, obtaining results by averaging the behavior of all individual components, is called statistical mechanics. The subject differs from thermodynamics chiefly in the mode of approach; thermodynamics considers the system as a whole and so does statistical mechanics, but in the thermodynamic process individual components are forgotten. Thermodynamics says that a given experiment must give a certain result, while statistical me-

chanics says that it will very probably give this result. In some significant instances, statistical mechanics predicts behavior quite foreign to anything in thermodynamics.

The study of heat as a form of energy is the subject matter of thermodynamics. Investigations made in this field have resulted in the establishment of two of the most important generalizations known to physical science. These are called, respectively, the first and the second laws of thermodynamics.

The first law is the principle of the conservation of energy: no longer the older principle as known to Newton, but including the discoveries of Mayer and Joule that heat is energy. The law is useful whenever a gas is heated or cooled, compressed or allowed to expand.

The first law gives the numerical relation between the energy (heat or work) supplied to the gas, and the resulting change of heat energy, pressure or volume of the gas. According to this principle, energy of any sort can only be obtained at the expense of energy of the same or different form. Perpetual motion of the type that would create energy is forbidden.

The second law, resulting from the work of Carnot, Clausius, and others, may be called the law of the availability of energy. Thus Clausius, in 1850, announced the principle that heat will not of itself flow from one body to another which is at a higher temperature. Thus the second principle forbids a kind of perpetual motion which would be allowed by the first law.

Inherent in the second law is the concept of entropy. This concept cannot be discussed at length in this chapter. Suffice it to say that when two bodies, one hot and one cold, are brought into contact so that they come to equilibrium at the same temperature, the entropy of the system containing these bodies has increased. The increase of entropy is a measure of the use of energy. As energy is used and becomes less available, entropy increases. For example, if the two bodies in the above illustration are respectively heated and cooled so that

the experiment may be repeated, other energy must be used. Fuel must be burned or work done, and there will be some limit to the number of times the experiment can be performed. Similar experiments are going on all the time, artificially or naturally, with the probable result that the future state of the universe will be a state of equilibrium at constant temperature, in which no work can be done and none of the energy be used. Naturally this conclusion is subject to revision in the light of future discoveries.

The laws of statistical mechanics and of thermodynamics are useful when large numbers of individuals are concerned. But there are some microscopic processes which occur singly or at best in very small numbers. These processes must be studied individually, and one should not be too surprised to find the laws of thermodynamics disobeyed. The fact that energy is conserved in macroscopic processes is in itself no proof that energy will always be conserved in single microscopic processes. If experiment shows that here again the conservation law is true, scientists will feel gratified. One should remember that the particle called the neutrino was invented in order to preserve agreement with the conservation of energy in certain atomic interactions, and that this particle was given properties and attributes which might well prevent its observation.

Chapter 2

PHYSICS BECOMES EXPERIMENTAL

THE PHYSICAL sciences are so completely dependent upon experiment that they are generally called exact sciences or experimental sciences. Theories or hypotheses must be tested before they are acceptable. The results of a carefully performed experiment on the other hand constitute a scientific fact, which will always be valid within the limitations of the experimental procedure. New theories such as relativity indicate the need for new experiments, and experiments often call for new theoretical interpretations. The experiment is good if performed with care, the theory is good if it is confirmed by experiment.

The emphasis on experiment has recently become so great that physical science limits itself to realms in which observation is possible. If the question is not available to experimental test, or is not likely to become so, then this question can be of no concern to physical science. It is true that both theory and experiment frequently push a little against the boundaries; witness the 200-inch telescope, and recent theories concerning the atomic nucleus.

Experimental science is a comparatively recent development. If science can be considered to have begun when men took a sufficiently great interest in their surroundings to notice natural phenomena and speculate on their causes, science is many centuries old.

It is difficult to say where natural philosophy stops and

physical science starts. The observation that amber may be electrified by friction constitutes one of the earliest physical experiments. Physics is then well over two thousand years old. This experiment however was an observation, not an experimental test of something. When theories and conjectures were actually tested under laboratory conditions the modern era of physical science was on its way.

Physics has been an exact or empirical science for something over three hundred years, or for about one eighth of its lifetime as measured from the electrification of amber. Because of the power of a truly exact science, the rapid advances made during the last three centuries have no counterpart in the earlier period. The very fabric of modern civilization is a result of modern science. All of Aristotle's learning would not have enabled him to construct a telephone.

Thales of Miletus, who lived about 600 B.C., may be said to have been the first physicist, although he would not have used the word. Situated in what is now Asia Minor, Miletus was at that time an outpost of Greek civilization. Thales inherited the elementary geometry and astronomy of the age, which had been developed principally in Egypt, Babylonia, Assyria, and among the Phoenicians, to fill utilitarian needs. Early peoples had needed a smattering of geometry in order to lay out plans for their buildings and to survey their land; this was especially true in Egypt, where periodic floods of the Nile wiped out boundaries between adjoining estates. The Phoenicians used their knowledge of the stars to aid them in the navigation of their trading vessels. These early peoples noted the passage of time by the motions of the sun and moon, and knew that the planets differed in some way from the other heavenly bodies. Certain regularities in the motions of these bodies had been noticed and Thales was able to predict a total eclipse of the sun, which gained for him a great deal of fame. However, his classification as a physicist rests not on his study of the heavens but upon the results of the first recorded electrical observation. Thales noticed that

a piece of amber when rubbed with fabric acquired a new property it had not previously possessed. The rubbed amber had the power of attracting light objects and of holding them to itself. We now regard the amber as having been electrified by friction and as drawing pieces of paper or pith to itself by electrical attraction. In fact, the word *electricity* is derived from the Greek word for amber.

Thales of course knew nothing of the causes underlying his observation, nor did he realize the relation between his rubbed amber and a flash of lightning. Hence it can not be said that he was a true experimental scientist—he merely noticed what he saw. An experimental scientist, according to the modern conception, would have enunciated a definite question which he would have put to nature to be answered. He would have reasoned that a piece of amber might be expected to acquire different properties if it were rubbed, then he would have made the test and observed the result. If his suspicions were realized, he would next have tried other substances to see if the same treatment would produce the same results and, to complete the picture, he would have tested the amber in other ways to find out whether this new phenomenon might be effected by other means.

Thales was an able engineer for his day and was employed in the construction of municipal works. He attempted to discover some underlying cause, some unifying principle for all things, which indeed is still one of the chief aims of a scientist; but to Thales the one most fundamental thing in nature appeared to be water.

Pythagoras lived from approximately 582 to 500 B.C. He established what has come to be known as the Pythagorean school, a sort of fraternity in which pupils and master worked and studied together. The Pythagoreans were interested primarily in the abstract theory of numbers and sought for mathematical relations in nature. Their studies in geometry paved the way for the work of Euclid two centuries later; in fact, many of the propositions in Euclid's geometry were first

studied by Pythagoras. As a physicist, however, the latter is remembered chiefly for his researches in sound. His experiments with the monochord were among the earliest attempts to put a question to nature. The monochord is simply a single string, such as a violin string, tightly stretched between two convenient supports on a sounding board. A movable bridge permits changing the length of that portion of the string which is vibrating. In the case of the violin, the player's finger controls the length of the vibrating string, while the body of the violin is the sounding board.

Whether the monochord was suggested to him by Apollo's lyre, or by the musical sounds of hammering emerging from a blacksmith's shop, Pythagoras constructed the instrument and performed experiments to determine how the pitch of a musical sound varied with the length of the vibrating string. He discovered that the pitch was inversely proportional to the length of the string which was allowed to vibrate. Moreover, he found that those tones were most harmonious which were produced by string lengths proportional to each other as are the small whole numbers, one, two, etc. We can imagine his delight in finding such an intimate relation between music and his beloved science of numbers. But his experimental results were taken into a realm in which Pythogaras had no means for experimenting. He began studying the "music of the spheres," and decided that the distances of the planets from the earth must be in musical progression, related in some such way as were the lengths of the string on his monochord which vibrated to give harmonious tones.

Pythagoras did not recognize the difference between air and empty space, and it was left for Anaxagoras (about 500 to 428 B.C.) and his contemporary Empedocles to demonstrate this difference and to prove that air is a substance. In this proof they made use of water clocks. A water clock is a container for water, with a small hole near the top and another near the bottom through which the water flows or drips. Time is measured by the outflow of water. The observation was

that upon immersing the lower end of the vessel, water would not flow in unless the upper hole were open. A thumb held over the upper opening would prevent water from entering or, in fact, from leaving the vessel when the water clock had been filled and placed upon its stand. Water could not enter the vessel unless air could leave, and vice versa. Here was a clear differentiation between air and empty space. Anaxagoras also studied the breathing of animals, and observed the function of the gills of fish.

Anaxagoras was the first of the so-called atomists. He believed that in the last analysis all matter consists of minute, invisible bits of material which combine under the influence of such causes as love and hate to produce the objects of the physical world. His materialistic views concerning nature and creation made him extremely unpopular with the orthodox. The atomic conception was clarified to some extent by Leucippus, who spoke of the origin of things by the chance encounter of atoms in empty space. Democritus (about 460 to 370 B.C.) was the last and best known of the atomistic trio. All three lived in the Golden Age of Greek culture.

It must be remembered that to these men the atom was not the definite concept of modern physics and chemistry, even though the modern atom owes its name to them. The idea of an ultimate, indivisible particle of matter arose from speculations concerning the divisibility of matter. Could a drop of water, for example, always be divided into smaller and smaller parts, or was there a limit? Democritus knew that simple treatment would change ice to water, and water to steam, but that ice could not be changed to stone. He imagined that different kinds of atoms must exist. Atoms of stone combining with atoms of stone produce a stone, but atoms of stone combining with atoms of some other substance such as wood produce a substance different from both. The idea of atomicity also gave Democritus an explanation of the difference between water, ice, and steam.

Because of his zeal in teaching the new doctrine, Democritus

was the best known of the atomists. He had the modern scientific attitude of inquiry, of scientific doubt and demand for experimental verification of his theories. Although he had no means for experimenting with atoms, he saw the need for experimental testing of theories and did not teach his ideas of atomicity as absolutely true, a thing which can not be said of most of his contemporaries.

Aristotle, one of the great philosophers of all time, lived in Greece in the fourth century B.C. He was a pupil in Plato's famous academy but was in no sense a physicist. The teachings of both Plato and Aristotle were unscientific in the modern sense; the great importance of Aristotle in the history of scientific thought is the influence of his work for centuries and the struggle of science, in its efforts to become exact, to free itself from the ball and chain of Aristotle's writings.

Aristotle wrote many books on science. He made observations in that he watched nature and asked himself the reasons for what he saw, but his observations told him that which he had known beforehand must be true. When he put the question to nature, if the answer seemed to contradict his preconceptions he regarded it as a matter of interpretation. In the search for truth, metaphysics was the ultimate source of knowledge.

The power of Aristotle's logic was immense. His writings were so persuasive that for centuries after his time his books constituted the final authority in all things scientific. This fact was strikingly true in the case of astronomy; when observations began to tell new facts about the planets and other heavenly bodies, savants merely shook their heads—it was not according to Aristotle.

The age of logic was a fertile ground for the growth of Euclid's geometry, characterized by reasoning from the known or, as we would say, from the assumed to the unknown. The same method was used by Aristotle, but in his case the *known* did not rest on experimental grounds. Today we find the theoretical physicist reasoning from the known to the un-

known, but the known is an experimental fact and the result of deliberation is not regarded as true until fully verified by experiment; and the more numerous the experimental proofs the better it is for the theory. The modern theorist depends on mathematical methods which have been proved sound and only occasionally resorts to pure hypothesis or intuition, though intuition plays a major role when it is inspired. Aristotle used a great deal of intuition, but his conclusions were not adequately tested. The validity of Euclid, besides his accurate logic, rests on the experimental facts which were his starting points. He himself would have had no difficulty in verifying all his axioms and postulates by experiment. While it is doubtful whether he ever consciously sought experimental justification for his statements, many such verifications constantly stared him in the face. He could easily see that the shortest distance to the public square was the straight line between the square and his house.

Archimedes lived during the third century B.C. Both Euclid and Archimedes are associated with the Alexandrian school. Aristotle had been a tutor of Alexander the Great, and after Alexander had conquered Greece the center of learning and culture moved to the new city of Alexandria, in Egypt. The quest for knowledge continued, now led for a time by Archimedes, a man of wide interests and a practical turn of mind.

Archimedes carried forward the development of geometry and laid the foundations for theoretical mechanics and the calculus. He had more interest in applied science than did Euclid, and studied the lever and other simple machines, giving mathematical explanations of their use. He also constructed engines of war and a spiral screw to lift water in a tube, and used ropes and pulleys to move ships along the ground preparatory to their launching. His name has lived in the annals of physics not so much for his engineering accomplishments as for his investigations in hydrostatics and the laws or properties of bodies floating or submerged in liquids. He is noted in particular for one famous experiment,

that made to determine whether a quantity of silver had been substituted for some of the gold supplied a goldsmith by his king, Hiero, for the making of a crown. The law of physics which is involved is now found in all textbooks of elementary physics and is called the principle of Archimedes.

We have no direct evidence that Archimedes was an experimental scientist but he must have performed many experiments, particularly on the lever, in order to design and construct his engines of war which were designed to hurl great stones at the enemy. It is inconceivable that he could have constructed his water screw without experimentation. The study of the crown was a definite measurement of an actual quantity, which is the best example of scientific observation. These things were regarded in his day as feats of engineering and gained him great renown.

According to the principle of hydrostatics stated by Archimedes, a body submerged below the surface of a liquid will weigh less than in air, and this buoyant decrease in weight is exactly equal to the weight of the liquid displaced by the body, or the weight of a volume of the liquid equal to the volume of the body. A floating body loses all its weight, otherwise it would sink. Since gold is more dense than silver, a gold crown weighing one kilogram in air would displace less water and hence lose less weight when submerged, than one of the same weight made from an alloy of gold and silver; the volume of the gold crown would be less than that of the crown made from the alloy.

Following the time of Archimedes, physics and, in fact, all science was at a virtual standstill for centuries. Roger Bacon, who lived in England during the thirteenth century was principally an alchemist, although he also performed experiments of a physical nature. In particular, he studied the simpler laws of geometrical optics. Although he realized the necessity for the experimental method in physics, he did not advance knowledge to any great extent and was persecuted for his

alleged magic powers. He would have been a true physicist in the modern sense had he lived a few centuries later.

The fifteenth century A.D. is memorable among other things for the discovery of America and the invention of printing. The work of the Italian, Leonardo da Vinci (1452-1519), gave hints of the scientific awakening which was soon to follow. Artist, engineer, scientist, Leonardo eagerly read the works of Archimedes and performed experiments in engineering and physics. He recognized the impossibility of perpetual motion and regarded the physical sciences as practical applications of the truths of mathematics. He studied the actions of simple machines such as the lever, examined the laws of falling bodies, and studied the principles of hydrostatics and hydrodynamics. He recognized the principle of inertia, later to be incorporated in Newton's laws of motion, and performed experiments in sound and light, noting the close relations between reflections and echoes.

The scientific awakening does not date from the time of Leonardo, partly because the time was not ripe, partly because he did not publish his work but left only his notebooks. He was an oasis in the desert of scientific misbelief which had lasted since the time of Aristotle. In all this time the writings of Aristotle had been the guiding beacon for all true believers; and the true believers, fortified by the authority of the organized church, were nearly unanimous. If one wished to know anything about nature, he had to turn to the writings of Aristotle.

It was inconceivable that this state of affairs should continue indefinitely. Science had been at a standstill for many centuries. Truths, so-called, had been established and were thought to be known with certainty. Scientific beliefs as well as religious beliefs were in the hands of the church, with Aristotle as the revered prophet of all that was true in science. An unbelief in science was nearly as serious as an unbelief in religion, and in those days heretics did not live to be old men.

In a sense, the religion of the day was dependent upon cur-

rent scientific belief. An acceptance of the Copernican idea in which the earth lost its commanding position at the center of the universe might well be the beginning of the end for dogmatic religion.

Galileo Galilei was born at Pisa, Italy, in 1564, the same year in which Shakespeare was born. At the age of thirteen Galileo was taken to Florence (he was of Florentine descent) and placed in a school nearby. When he was eighteen he returned to Pisa to enter the university. During the four years in Pisa, followed by four more at Florence, he was diligent in the pursuit of knowledge. He mastered contemporary science to such a degree that at the youthful age of twenty-five he was asked to join the faculty at the University of Pisa, where he was to teach mathematics.

This man who was destined to shake the world out of its scientific lethargy was a contemporary of Tycho Brahe, Kepler and Gilbert. Tycho the astronomer had cataloged the positions of stars and planets with accuracy, and his student Kepler was able to correlate these observations and to state the famous laws of planetary motion. With the help of these laws of Kepler, the circumnavigation of the globe by Magellan, and the astronomical observations made by Galileo, the Copernican theory was finally triumphant.

Gilbert, physician to Queen Elizabeth, is remembered for his publication of a volume devoted to magnetism. It was he who chose the name "electrification" to be applied to the property acquired by amber when rubbed. Gilbert found that glass rods could also be electrified by friction. He studied the properties of the lodestone, or natural magnet, and knew that unmagnetized iron could be magnetized by its use. His most noteworthy experiment was his proof that the earth is a magnet, a proof he achieved by cutting a lodestone into the shape of a sphere and showing that the magnetic field surrounding this sphere was similar in form to that surrounding the earth. A unit occurring in electromagnetism has been named after him, but his name is rarely heard today.

Others beside Galileo were learning to use the method of direct appeal to nature, the experimental method. The name of Galileo stands out because of the fundamental and controversial nature of the subjects he chose to investigate, and the courage and clearsightedness with which he investigated. Tycho recorded what he saw and no one was in a position to argue with him as to the validity of his observations. Gilbert also put down what he observed; his findings were new but did not contradict what was generally believed, with the exception of the belief that diamond could be magnetized, which he easily disproved. Not much was at stake in these questions, nor were any disproofs of the doctrines of Aristotle involved.

As a young instructor at the University of Pisa, Galileo wrote on dynamics with great clarity of thought. His conception of dynamic quantities such as velocity and acceleration would be acceptable today. In the fields of higher learning he had been to a large extent self-educated, reading the available works of science and philosophy, and he soon became a fearless and independent thinker. His eyes were open while those of most of his colleagues were closed. Seeing a stone thrown in the air, he would watch its path and speculate on its behavior. It could not fall in the manner he observed if the old dynamical concepts were true, and he was perplexed by the discrepancy between what he saw and what he had learned from books. Others did not see the difficulty. If the stone did not appear to fall in the prescribed way, his eyes must have been mistaken; men's eyes had been deceived before and might be again. They would thank him to read the books and learn his lesson and, in any case, stop bothering them.

It is often dangerous to attack recognized authority, even though there be reason in the attack. But Galileo had the courage of his convictions; he knew what the books had to say and he felt they were wrong. He had no fear of the sages who tried to intimidate him. As an opinion, his was one against many and could not prevail. But there was another way. Nature had spoken to him through the falling stone. Could

he not ask nature to speak so clearly, so definitely, that others might hear and understand? He believed he could, and this decision marks the real birth of the experimental science of physics.

It had been believed that bodies dropped from a high place would fall with different speeds, the heavier ones falling faster. Since most things that are dropped do not fall from any great height, and since in any case air resistance affects the motion, the error had not been apparent. If stones of different size had by chance fallen together and if some learned man of the day had seen them fall, he would probably have concluded that since the heavier one must fall faster, the lighter one must have been dislodged first. If the stones were dropped from the hand to the ground, the fall would be so short that either theory would fit the observations.

Galileo had noticed that stones thrown into the air did not behave as if the heavier ones fell more rapidly. An unverified story persists that he decided to drop two bodies of different weight from the top of the leaning tower of Pisa to prove that the bodies would fall together. If this experiment was actually performed, with suitable precautions, the result would have been definite and obvious. Other experiments on spheres rolling down inclined planes were sufficiently definite in their results to convince all with open minds. But those who should have been convinced turned again to the statement that heavier bodies fall faster than lighter ones. There it was, as they had read many times. Galileo was an infidel, an upstart who questioned the precepts of Aristotle, and he should be removed. With the faculty against him almost to a man, he retired from the university in the middle of the term for which he had been engaged.

The results of these experiments were later incorporated in Newton's second law of motion: If a force acts on a body and accelerates it, then the force is equal to the product of the mass of the body and the acceleration which is produced: $F = m \times a$. In the experiments of Galileo the masses were differ-

ent; but since acceleration is equal to force divided by mass, the force on the heavier body (i.e., its weight) was greater than that acting on the lighter body in the same ratio as its mass was greater than the other, and the acceleration, the ratio of force to mass, should be the same for both. The acceleration of gravity at one particular locality on the earth's surface is the same for all bodies, heavy or light. Even a coin and a feather fall together in a vacuum.

It is true that the results of Galileo's experiments were not accepted at once, but that does not detract from his greatness. He saw more clearly than had anyone before him the necessity for the experimental method of investigation, and he actually performed experiments. It is probable that if Galileo had not shown such insight and courage, others would have done so. The advance was bound to come and would eventually have forced itself upon the world, perhaps suddenly, perhaps gradually. Galileo's work inspired disciples who were to carry on, and their work was easier because of his.

Forced to leave Pisa, he became a teacher of mathematics at Padua, where he found a group of men more broadminded than had been the case at Pisa. His lectures covered a wide range of subjects in mathematics, physics, and astronomy. Here he invented the air thermometer, the first accurate means of measuring temperature. Several years earlier, at Pisa, he had as a young man discovered the law of the pendulum. Watching the swinging of the hanging lamps in the cathedral, he had noticed that the time of each swing depended only on the length of the pendulum and was the same whether the magnitude of the swing was large or small.

At Padua he constructed his historic telescope. Although he is said to have obtained the idea from Holland, he certainly made the first telescope capable of astronomical use. His discovery of the satellites of the planet Jupiter is too well known to require more than mention. He also saw spots on the surface of the sun and measured the sun's period of rotation. Possibly more important for the progress of scientific knowl-

edge was his discovery that the planet Venus exhibited phases similar to those of the moon. This in fact had been a formidable stumbling block for the Copernican theory. It had been argued that if the planets move around the sun, Venus should undergo changes in phase, at times appearing fully illuminated, at other times a crescent. The Copernicans had answered that no doubt such changes occurred, though invisible to man with his puny powers, but that providence was kind and a time would come when man would see what was certainly waiting to be seen. Now the time had come.

Galileo's fame had by this time spread far and wide, and an invitation came for him to move to Florence under the auspices of the Duke of Tuscany. It would have been better for him to have stayed at Padua, where thought was comparatively free and minds unfettered. The atmosphere into which he moved was a learned and scholastic one, but for a man of Galileo's stature it was to be a prison, for Florence was under the rule of the church, with the credo that science must exist solely for the sake of religion, and that scientists must act accordingly. The Copernican theory had been banned, and Galileo was prohibited from teaching or writing about it except with church-imposed restrictions taking the power from his argument. The restrictions became more and more severe, ending in the famous trial and Galileo's denial, about which so much has been written.

What would have been gained had this old man of seventy become a scientific marytr? He would not thereby have taught anything to his persecutors. As to those who might have been convinced by this course, most of them had already been convinced by the evidence he presented. A few broadminded ones had shared his inspiration and were waiting to carry forward the torch where Galileo could not follow. He had already done more than anyone before him to advance the principles of science. He knew that the age was not ripe for further advances. He suffered personal humiliation but that had been a common thing in his life. The results of his experiments

could not be altered by anything that he or anyone else could say. Others would construct telescopes, larger and better ones, and would see things he had not seen even in the depths of his fertile imagination. Truth is truth and must prevail, even over those bigots who adapted this saying for their own uses. If he could live he might learn more of the wonders of nature. He could turn again to the study of mechanics, and let the ferment of his astronomical discoveries work on the minds of men. Who can say that he should have chosen death?

Chapter 3

LIGHT WAVES

LIGHT IS the most common of all natural phenomena. Its existence is obvious even to the lower animals. One does not have to travel to find it, nor explore or dig for it. It is everywhere and there is more than enough for everybody. But in spite of the long ages during which light has been known, and the centuries in which it has been studied, science has only recently ceased to regard light as incomprehensible or mysterious.

It is quite apparent to anyone that light generally travels in straight lines, so much so that the significance of this fact probably failed to impress early scientists. To wonder about this observation would be like wondering why when one walks in the direction ahead of him, he moves forward. Animals also move in straight lines when they wish to go somewhere and nothing is in their way.

Many ancient writers have mentioned light. Euclid is believed to have studied the subject to a considerable extent. In the work on optics which is attributed to him appears the statement that light travels in straight lines, as well as the opinion that vision results from something the eye sends forth as a messenger. Pythagoras and other writers, including Democritus, inclined to the opposite view that vision is caused by the impact on the eye of small particles sent out from the object which is seen.

Euclid studied the reflection of light from plane and curved

mirrors and realized that the incident and reflected rays make equal angles with the mirror surface. He also recognized the existence of a focus for concave mirrors, enabling the rays in a beam of sunlight to be sufficiently concentrated by the mirror to set fire to inflammable objects; further, he knew that a coin placed at the bottom of a vessel appears to be raised when the vessel is filled with water. Ptolemy, in Egypt, during the second century A.D., studied the refraction of light in the atmosphere and in liquids, and recorded the fact that when the light passes from one medium to another the direction of the ray is altered at the surface between the media and the angles of incidence and refraction are proportional, no matter how the incident ray strikes the surface. At a somewhat earlier date Hero had written that a ray of light reflected from a mirror will always choose the shortest possible path. In all these statements can be detected concepts which later have been combined into the science of geometrical optics.

In Arabia, about 1030 A.D., Al Hazen performed experiments with mirrors and lenses. He studied the magnifying power of curved mirrors as well as lenses, and recognized the existence of spherical aberration, a defect of optical instruments which often prevents the formation of an exact focus. In his work occurs one of the earliest attempts to discover the construction and optical properties of the human eye. His writings were studied by Roger Bacon, who in addition to his other efforts discussed the possibility of constructing a telescope, although it is doubtful if he ever actually made one. In addition to examining the properties of lenses and mirrors, Bacon enunciated a theory of the formation of rainbows.

Leonardo, whose experimental work has already been mentioned, investigated the structure of the eye. From the similarity between sound echoes and optical reflections he was led to compare sound and light, and wondered if light could not also be a wave motion. He probably imagined the same sort of wave motion as is responsible for the transmission of sound energy, with the direction of vibration parallel to the direc-

tion of propagation. The later idea of a transverse vibration in an elastic ether was much too subtile for any contemporary of Leonardo and, in fact, was not demanded or indicated by any available observation.

In the University of Leyden, Snell studied the passage of light from air to water and in 1621 was able to state correctly for the first time the law of refraction. This law is now called Snell's law; the modern form of the law, given by the mathematician Descartes, states that the ratio of the sine * of the angle of incidence to the sine of the angle of refraction is a constant for any two media in contact; the constant is called the index of refraction. Descartes was in error in believing that light travels more rapidly in the denser medium, water, than in the rarer medium, air. Fermat, a contemporary of Snell, correctly assumed that the velocity of light was less in the denser medium, and derived Snell's law by the use of what has come to be called Fermat's principle, that when light travels from one place to another, whether reflected or not and whether remaining in the same medium or passing from one to another, it will arrive at its destination in either the shortest or the longest possible time. It is today a simple matter to derive all the laws of reflection or refraction of light by the use of Fermat's principle. The next step was made at the end of the century by the Dutch physicist Huygens, who saw that the change in velocity must occur at the surface and assumed that the index of refraction was a measure of the relative velocities of light in the two media.

At this early stage in the theory of light, the only available experimental evidence, beside the perplexing polarization of light by crystals, which was discovered by Bartholinus in 1670, was that provided by Snell and others who had studied reflection and refraction. A theory of light was considered satisfactory if it led to Snell's law. For example, Newton in 1687 explained the facts of refraction on the basis of his cor-

* In a right triangle, the sine of one angle is the ratio of the side opposite the angle to the longest side, or hypothenuse.

puscular theory, in which light was supposed to consist of small particles which in their motions along straight lines finally struck the eye and produced the sensation of sight. In order not to deviate from Snell's law he had to assume that the particles moved with greater speed in water than in air, an assumption which could neither be proved nor disproved at the time.

Newton's experiment with the prism, however, constituted a great forward stride. It had been believed that white light was changed in its fundamental nature by passage through a prism. Earlier writers had associated the colors of the rainbow in some way with refraction, but it was not until Newton's experiment that anything definite was known. He allowed sunlight to enter his laboratory through a small hole in a window shutter. The narrow ray of light passed through a glass prism and fell on a screen; the image on the screen was no longer white, but was spread out in a band of colors arranged in the same order as are the colors in the rainbow. Were the colors caused by the prism, or were they inherent in the light itself? Newton, with that remarkable scientific insight for which most modern scientists would mortgage their worldly possessions, felt that the white light consisted of a mixture of colors which had merely been separated by the prism. A simple experiment would furnish proof. He made a small hole in the screen just where the red part of the band of color fell, so that a ray of red light passed through the screen. Behind the screen he arranged a prism in the path of the red ray, which passed through the second prism and fell upon a second screen in a patch of red. The direction of the ray had been changed but the prism had not altered the color. To complete the proof, Newton placed the second prism between the first prism and screen. The second prism, if placed in the proper position, undid the work of the first, and rays separated by the first prism were combined again by the second: the spot of light falling on the screen was white.

Newton had proved that white light is a mixture of colors,

and that rays of light of the various colors are bent by varying amounts when passing obliquely from one medium to another of different density: each color has a different index of refraction. He painted the colors of the rainbow, or his spectrum, on a disc of cardboard and rotated the disc rapidly; the eye was thus forced to look simultaneously at all the colors at once and the disc appeared, not colored, but light gray, just as if the disc had been painted alternately black and white.*

These early scientific discoveries may seem simple to those of us who have grown up with a knowledge of scientific discoveries of the recent past. They did not seem so simple at the time they were made. Some day school children will be amused by the idea that their ancestors found Einstein perplexing.

Newton's discoveries relating to color and refraction were later to have an important bearing on the wave theory of light, but at the time there was nothing in the experiments to suggest that light is a wave motion. We know that color is determined by the length of the light waves, red light having a longer wave length than blue light. Newton explained everything on the basis of his corpuscular theory, which he had invented to satisfy the requirement that light must travel in straight lines. The later proof on the basis of wave theory of the rectilinear propagation of light was to be one of the greatest triumphs of the theory.

One of Newton's few mistakes had interesting results. In studying the deviation (change of direction) of light by a prism and dispersion (breaking up of light into a spectrum), he believed that one was always proportional to the other, a fact which is true for some substances, possibly those he used, but not for others. He was attempting to construct an object glass for a telescope which would be truly achromatic and bring light of all colors to the same focal point to form an un-

* One must note the difference between mixing colors with the color disc, and mixing paint pigments; the two methods are essentially different and should not always give the same result.

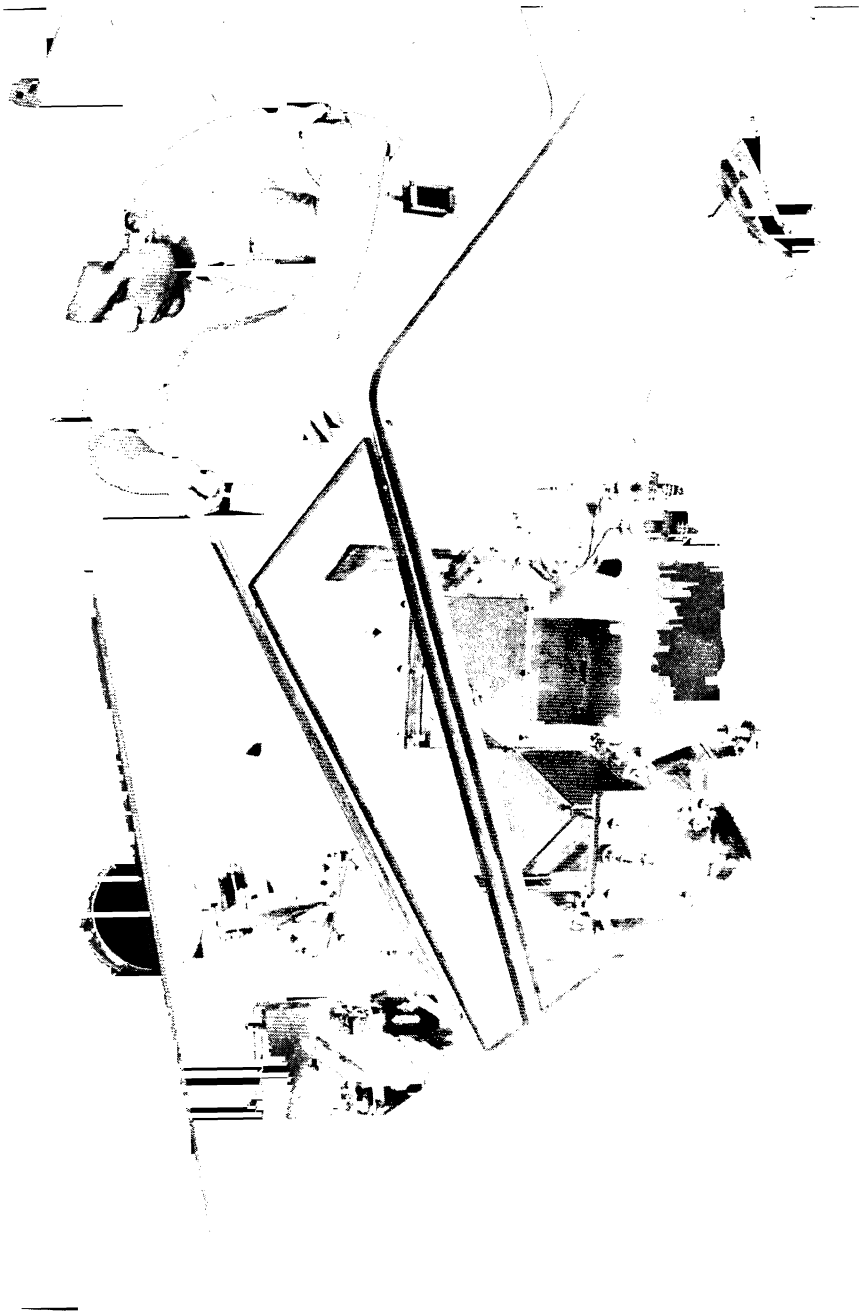
colored image. To make such a lens, two lenses of different refractive power must be fitted together so that the dispersion of one is nullified by that of the other, as in Newton's experiment with the two prisms. The deviation of the combination however must not be destroyed, otherwise there would be no focussing action. Newton believed that when the dispersion was balanced out the deviation would also disappear. He therefore turned to the making of reflecting telescopes which are not troubled with chromatic aberration as are telescopes made with lenses. His reflectors are historic instruments. Probably astronomy lost little by this emphasis on reflectors as contrasted with refractors, since both have their merits. It may also be true that Newton found it easier to grind a mirror than a lens, and good optical glass was not available in his day.

So far no experimental evidence clearly demanded a wave theory of light, and the corpuscular theory had been stretched sufficiently to explain all the observed facts of reflection and refraction. Now a new phenomenon appeared. The Jesuit Grimaldi, at Bologna, whose work was published after his death in 1663, noticed that when light from a distant source passed a sharp object, the shadow of the object was not clearly defined: alternate light and dark bands appeared at the edge of the shadow, shading off to darkness within the shadow. Here was a case in which light moving in a single medium did not travel quite along a straight line, being bent somewhat into the shadowed region. The phenomenon observed accidentally by Grimaldi and called "diffraction" today constitutes one of the strongest verifications of the wave theory. Newton tried to explain the bending of light by diffraction in terms of a fictitious attraction of the light particles by the object. The real stumbling block in this attempt was the fact that within the geometrical shadow there was not a single light band but several such bands fading finally into darkness; this necessitated the rather elaborate assumption of some sort of periodic attraction at the edge of the object cast-

ing the shadow. The difficulties of the corpuscular theory were accumulating, and soon the wave theory was to prevail.

Hooke, in England, was the next to study diffraction. He had been a contemporary of Grimaldi but lived for some forty years after Grimaldi's death. Hooke studied the diffraction bands in shadows and became interested in the colors appearing in thin soap films and films of oil on water, colors which are often arranged in recurring bands similar to the diffraction bands seen in shadows. Hooke made no important contribution to the theory of light, nor did he devise experiments which could bear witness either for or against the theory.

As one would expect, Newton immediately became interested in the new discovery. He was to play a rather peculiar role in the development of the wave theory. In the first place he studied and discovered facts which are now regarded as among the best proofs of the wave nature of light. But he so persistently taught the truth of his corpuscular theory that for over a hundred years it was impossible for men of smaller attainments to prevail against his exalted position in the scientific world, even though some of them clearly saw the necessity of a wave theory to explain experimental results. It can not be said that Newton foresaw the modern corpuscular theory of radiation, the quantum theory, in which valid results of the wave theory are included. But Newton had remarkable scientific insight, and one wonders what would have happened if other facts had pointed towards the validity of the quantum theory at the time when his corpuscular theory was strongest; the wave theory in the pure form which lasted for so many years might never have appeared. Newton's theory of gravitation is still valid except where large masses or observations on a cosmic scale indicate the necessity of the refinements of relativity. But his corpuscular theory was completely displaced, to be replaced by the wave theory in pure form and later by a theory in which both the wave and corpuscular nature of radiation and, indeed, of particles of matter such as electrons, combine to give what is believed to be an accurate



picture. Newton rejected a wave theory which assumed longitudinal light waves, and polarization of light can not be explained on such a theory: only transverse waves can be polarized. Accordingly, the corpuscular theory, with all its difficulties, seemed to him the logical choice.

Newton experimented with the formation of colors in thin films of transparent material. In one of his classic experiments a glass lens of large radius of curvature is held in contact with a plane glass plate. The two glass surfaces touch at one point, while everywhere else they are separated by a thin film of air whose thickness increases with radial distance from the point of contact. If light of a single color such as yellow sodium light falls on the glass, one sees concentric rings surrounding the contact point. These rings are known as Newton's rings, and are dark and light when monochromatic light is used for illumination, or multicolored if white light is used. The rings move outward as the glass pieces are pressed together, and crowd inward as the pressure is removed; in general they tend to move away from the point at which pressure is applied.

Newton recognized that these recurrent rings depend in some way on the changing thickness of the air film, and that this dependence must be in some way periodic, as indeed is true of the diffraction bands in the shadow of a sharp object. This periodicity would seem to demand some sort of wave theory. But Newton interpreted his observations in terms of his corpuscular theory and believed the effect was related to the relative ease with which the particles of light could move through the various parts of his apparatus. He measured the thickness of the air film at each succeeding ring and found a recurring quantity which actually is related to the length of a light wave. In fact he obtained a very good measurement of the wave length of one color of light—but he thought he was measuring something quite different. He did however prove that something connected with the propagation of light must be periodic. In spite of the fact that he regarded his explana-

tion as support for the corpuscular theory, his observations are now regarded as excellent proof of the wave theory.

Evidence in support of the wave theory was accumulating. Römer had just announced his discovery, from observations on eclipses of the moons of Jupiter, that the speed of light is not infinitely great, but finite and measurable. Newton had discovered a periodicity in light without seeing what this discovery implied. The wave theory was now injected into the argument in an explicit manner by Huygens. Assuming space to be filled with an elastic medium called the luminiferous (light bearing) ether, he discussed the possibility that light might be a wave motion existing and travelling in the medium. The simple facts of reflection and refraction could thereby be deduced, and a further advantage was apparent in that elastic waves in an elastic medium always travel with finite, never with infinite, speed.

It had been easy to assume that light must consist of a stream of particles, since light travelling in a single medium and not passing too close to an obstacle always moves in straight lines; Newton's laws of motion indicate that a material particle which is in motion in a straight line will continue so unless a force causes it to deviate. Huygens now proceeded to prove that in fact the wave theory demands that light should travel in straight lines unless it goes from one medium to another, or suffers diffraction. In this proof he made use of what we call Huygens' principle.

Imagine that a series of ripples is moving forward on the surface of water, and that in the path of the oncoming ripples is placed a plane obstacle having a small hole. As the ripples, which by now are nearly straight since they have travelled a long way from their source, meet the obstacle they are stopped, except for a small portion near the hole. Water in the opening is set in vibration and a new train of semicircular ripples starts out from the opening as a source.

The hole in the obstacle is now enlarged considerably. When the advancing ripples meet the large opening, all the

water in the opening is set in vibration and each particle acts as a new source of semicircular waves; but these waves interfere with each other in such a way that a straight ripple (plane wave) advances beyond the opening. The new wave is the envelope of all the little wavelets. The obstacle can be removed completely, and the ripples allowed to move without hindrance across the surface—but each ripple sets the water in motion, each particle acts as a new source of wavelets, and the envelope of these wavelets is the next ripple. The ripples move forward in straight lines just as plane light waves move forward along straight lines which are perpendicular to the wavefronts. In the case of light it was assumed that particles of the hypothetical ether were set in vibration.

Huygens' principle, based entirely on the assumption that light is wave motion, can thus account for rectilinear propagation. The principle has been found useful in the theory of the diffraction grating, now so widely used in spectroscopy, as well as other devices most of which were unknown to Huygens. It has recently become apparent that something akin to Huygens' principle applies under certain conditions to the motion of material particles, a fact which to Huygens would have seemed fantastic.

The seeds of the revolt had now been sown. The plant was to grow rapidly under the care of Thomas Young and was soon to burst into luxuriant bloom in the hands of the French student Fresnel.

Young was an English physician who through his studies of the human eye had become interested in Newton's work on the nature of light. He also knew of the work of Huygens. He was twenty-eight when in 1801 the idea for which he is famous came to him, an idea which proved to be a triumph for the wave theory and its adherents.

We return for a moment to our water surface which is now free of ripples. Let us drop two small pebbles into the water, being careful that they fall together. Two sets of ripples will be produced and each will advance across the water surface

as if it had exclusive right of way—until they meet. Then an interesting thing happens. Whenever a crest from one set of ripples meets a trough from the other the water surface is urged both upward and downward at the same instant and, not knowing which ripple to obey, obeys neither and remains quiescent. The ripples are passing the point in question but the water is not disturbed. At a nearby point crest may fall upon crest and the water is doubly urged upward; at this point the water is displaced. As a result, the interference of the two trains of ripples produces a stationary pattern on the surface of the water, with some points moving periodically up and down and others remaining undisturbed. The same thing can be demonstrated even better if the source is a continuous one, such as two pins fastened to the prongs of a vibrating tuning fork. In order to produce an interference pattern there must be a relation between the two vibrating sources—random agitation of the water will not produce a stable interference pattern.

Young applied the idea to light waves. If Huygens' ideas concerning the nature of light were true and light really consists of waves, it should be possible to make two trains of light waves interfere with each other. Light must come from two sources having a constant phase relation; two candles would not be suitable. But light from a single candle might illuminate two pinholes in a screen, which would act as secondary sources, each sending out wavelets in accordance with the principle of Huygens. These wavelets interfere and produce a pattern of alternate light and dark bands on a suitable screen or in a magnifying eyepiece.

A new theory is often accepted, not because older theories can not account for what is observed but because the newer theory can explain the facts in a simpler manner, with fewer hypotheses and assumptions. Thus the Copernican idea of the solar system was not the only one capable of describing the apparent motions of the stars and planets. The older system was overburdened with a complex set of epicycles which grew

ever more complex with each advance in observational knowledge. The Copernican system was simpler, was in agreement with every observation, and accordingly displaced the older one. In the same way it was becoming more and more difficult to explain optical observations on the basis of the corpuscular theory of light. When men like Young showed the gain in simplicity, and therefore plausibility, with which the wave theory could account for observed facts, the end of the corpuscular theory was in sight.

As is often the case, the transition was not too rapid. In the meantime Young studied the formation of color in thin films in attempts to produce additional evidence for the wave theory. His studies of the diffraction of light by single narrow openings led him to an error which is made today by nearly everyone who studies diffraction for the first time, in believing that the diffraction pattern obtained should be similar to the interference pattern produced by a pair of small openings. The work of Young was rejected by many on the grounds that the wave theory could not account for the results obtained in this rather simple experiment. That the wave theory can account for these results with complete satisfaction will presently appear.

Young's explanation of the formation of colors or interference bands in thin films was and still is valid. Light waves reflected from the upper and lower surfaces of the film will interfere in a manner depending on the angle of incidence, the thickness of the film, and the index of refraction. Sometimes certain colors are nullified and the other components of white light remain. Bands result from a changing thickness of the film, as in the case of Newton's rings. It was a triumph for Young to be able to relate these phenomena, as well as those occurring in his experiment with the two sources, to the new wave theory.

The time was ripe for some fertile genius to seize upon the accomplishments of Huygens and Young and carry the wave theory to such a point that its acceptance would be universal.

The genius turned out to be the French scientist Fresnel, who carried the theory to so many triumphs that in the realms of science to which it applies it has remained practically unchanged to the present day. As far as geometrical optics, interference, and diffraction are concerned, the wave theory of Fresnel will explain all observations.

Fresnel's first triumph was the successful explanation of Young's stumbling block, the diffraction of light by a single slit. Young had considered that light was reflected from the two edges of the slit, these two reflections taking the place of the secondary sources in Young's experiment. The difficulty was that in the diffraction experiment a dark band was observed in the position where a bright band should appear if the effect were caused by interfering light from two sources. Fresnel cleared the air by showing that the same result was obtained whether or not the edges of the slit could reflect light, and proceeded to show that the wave theory gave exactly the correct prediction. By means of a beautifully constructed argument he laid emphasis on wave fronts instead of sources, and explained not only the single slit experiment but also the diffraction of light by a sharp object. A light wave striking an object is partially obstructed; the remainder of the wave produces secondary wavelets according to the principle of Huygens, which wavelets interfere with each other to produce the diffraction bands. Fresnel's explanations have suffered little change during the hundred years or more since he first presented them.

The wave theory was thus becoming firmly established. It only remained to discover what sort of waves were involved and how their velocity depended on the medium in which they were travelling. A brilliant series of discoveries was now to provide these answers.

Polarization of light by reflection had recently been observed, rather accidentally, by Malus. Looking through a crystal at an image of the sun reflected in a distant window, he noticed that as he rotated the crystal the image varied in

brightness. Double refraction in Iceland spar had been known for some time; indeed Huygens had studied the formation of two images of a single object by crystals. As Malus rotated his crystal, one of the images increased in brightness while the other decreased until a certain point in the rotation was reached, when the situation reversed. The peculiar effect could not be due to the intervening atmosphere, for when Malus repeated the experiment with candle light reflected from water in his room the result was the same. Young was perplexed by this observation made by a strong proponent of the corpuscular theory, the more so since Young believed that light waves were longitudinal. But it was Young who finally hit on the correct solution. He saw that all observations could be explained on the assumption of a transverse vibration. The vibrations in a ray of light must be in the wave front, perpendicular to the direction of propagation. Fresnel independently came to the same conclusion. These men were so overjoyed that they overlooked the new demand that the luminiferous ether must now be an elastic solid, instead of a fluid, having properties which must impede the motion of the planets. For its solution this latter difficulty however had to wait until the time of Einstein and relativity, after which a number of inherited misconceptions, including some about the ether, were cast aside.

As a crude illustration of polarization by reflection, imagine a person dropping a stick on a desk top. He soon finds that the behavior of the stick depends on how it strikes the wood. A stick striking the surface horizontally has much more chance of bouncing without change of orientation than if it strikes vertically so that one end hits first. When a ray of light falls upon a glass surface at the correct angle, the reflected ray contains more of those vibrations which are parallel to the surface than those which are perpendicular, and this ray is partly polarized. The ray transmitted through the glass contains more of the other vibrations, and the two rays are polarized in mutually perpendicular planes. The interference of polar-

ized light produced questions which, when answered by Fresnel, Arago, Brewster, and Biot, gave strong support to the wave theory.

A single experiment remained to give final proof. Newton's form of the corpuscular theory had demanded that light must travel more rapidly in water or glass than in air, since the particles must be attracted to the surface in order to explain refraction and agree with Snell's law. Foucault, a French medical student, prepared to measure the velocity of light and to see whether Newton was right.

In Foucault's experiment, and similar experiments performed more recently, light falls on a rapidly rotating mirror, whence it is reflected along a tube containing air, water, or whatever substance is being investigated. At the end of the tube a stationary mirror sends the light back to the revolving mirror. But in the time it has taken the light to traverse twice the length of the tube, the mirror has rotated by a small angle and the light is now reflected along a different direction. With a knowledge of the speed of the rotating mirror and the length of the tube, as well as the angular displacement of the final ray, it is a simple matter to compute the velocity of light. Foucault was pleased to note that the measured velocity of light in water was less than that in air.

Thus the complete establishment of the wave theory dates from 1850, the year of Foucault's experiment. Although displaced in several ways by more modern theories, it is still supreme in the simple fields of geometrical optics and explains with complete satisfaction the observed facts of reflection, refraction, polarization, interference, and diffraction.

Chapter 4

HEAT AND ENERGY

In the development of every branch of modern science, conflicts have arisen whenever accumulated evidence has shown that accepted theories and concepts must be superseded by others. The theory of heat has undergone two such conflicts. At the conclusion of the first, heat was no longer regarded as the substance caloric, but was known to be a form of energy. At the conclusion of the second, heat radiation was no longer regarded as continuous.

The resolutions of these conflicts will be discussed in the present and future chapters. In the field of heat, as in many others, early experiments seem extremely crude when compared to modern techniques. When measurements become truly quantitative, theories become more exact. It often happens that a theory can be proved true or false by nothing less than the greatest experimental precision. The experiments which proved that heat is energy, not caloric, bear witness to the manner in which the development of theories and fundamental concepts wait upon the development of experimental techniques.

Heat was formerly regarded as a subtile substance called caloric, which was supposed to flow from hot bodies to cold bodies. Hot bodies contained more caloric than cold ones. No doubt the question as to how caloric could flow from one body to another was covered by the use of the word subtile. Scientists concerned with the wave theory had not been particularly

vexed by inconsistencies in the ether theory until these inconsistencies were emphasized by the performance of the Michelson-Morley experiment. As a matter of fact, the ideal heat engine of Sadi Carnot (1824), as well as Fourier's theory of heat conduction (1822), was discussed almost twenty years before it was generally recognized that heat and energy were the same thing. The Carnot cycle for a heat engine is still used to define the efficiency of a heat engine, even though the conception of heat has undergone a radical change.

The close relationship between heat and other forms of energy is apparent from the word thermodynamics, which includes the modern theory of heat. The idea of the conservation of mechanical energy dates from the time of Leibnitz and has undergone development since then; the theory of heat developed independently, until finally about 1850 both heat and mechanical energy were included under the conservation principle.

Before the invention of the thermometer, ideas of temperature must have been very crude indeed. Possibly six variations could be recognized: very cold, cold, cool, warm, hot, and very hot. It cannot be doubted that situations would arise in which one observer might think an object warm while another would think it cool.

The first thermometer was constructed, and the first measurement of temperature made, by Galileo shortly after 1600.

The air thermometer of Galileo, so called because the expansion of air with increase of temperature was the quantity observed, consisted of a glass bulb fitted to a long stem, the lower end of which dipped below the surface of water in a dish. Water rose in the stem when the bulb was cooled after having initially been heated. The height of the water level in the stem then became a measure of the temperature of the bulb, falling as the bulb was warmed and rising when it was cooled. Readings obtained by use of this thermometer were unfortunately also affected by barometric pressure as well as temperature, since a change in the pressure of the atmosphere

on the water in the vessel would affect the water level in the stem. Nevertheless Galileo was able to compare one temperature with another and to detect the higher body temperatures associated with sickness and fever.

A somewhat more reliable instrument was constructed a few years later by the French physician Rey, who substituted water for air as the substance whose expansion was to be a measure of temperature rise. His thermometer was not subject to variation with barometric pressure, but he failed to seal off the upper end of the thermometer tube, with the result that readings would change from day to day as water evaporated. It was left for pupils of Galileo, at Florence, to construct the first thermometer in which a liquid could expand into a closed and partially evacuated tube.

Temperature scales used with these early thermometers were quite different from those used today. A thermometer is calibrated by noting its reading at two temperatures which are chosen arbitrarily, then dividing up the intervening space into approximately equal intervals. It is to be hoped that the chosen fixed points can be considered constant, otherwise thermometers would not agree in their readings. The thermometric scales used by the students of Galileo were based on the temperature of snow on a cold winter day, and on the body temperature of animals. The upper calibration point was later changed to the temperature of melting butter.

The accuracy of a thermometer can be no better than the accuracy of its calibration. The constancy of the temperature of melting ice, at normal barometric pressure, was demonstrated by Hooke (1635-1703) who also is remembered for his studies of elasticity. The constancy of the temperature of steam over boiling water, again at normal pressure, was proved by Huygens, whose principal interest, however, was the wave theory of light. These standard temperatures are constant and readily duplicable, and they are used today in the calibration of thermometers.

It was left for Fahrenheit, during the early years of the

eighteenth century, to construct a thermometer of the type used today. His thermometer contained mercury in a glass tube sealed at the top and partially evacuated. The fixed points on his scale were the boiling temperature of water and the temperature of a mixture of ice and salt. These temperatures were called respectively 212 degrees and zero degrees, the intervening scale being divided up into equal divisions. The somewhat strange choice of the value for the upper temperature is explained by the probable assignment of 100 degrees to represent the temperature of the human body, a temperature which on modern and more accurate thermometers is called 98.6. Modern Fahrenheit thermometers are calibrated at 32 degrees and 212 degrees, the temperatures respectively of melting ice in contact with pure water, and steam above boiling water at normal atmospheric pressure. The Centigrade thermometer now used in scientific work and in some European countries is again based on these same standards, but temperatures of zero and one hundred degrees are assigned. This scale was adopted by Celcius in the middle of the eighteenth century.

For the greatest accuracy, modern thermometric scales are based on the expansion of hydrogen or helium in a highly accurate development of the gas thermometer. The expansion of mercury is not uniform throughout the temperature range of a thermometer; in fact no real substance does expand uniformly, and recourse is had to the nearest approximation to the ideal substance, the perfect gas. Two thermometers containing, say, mercury and alcohol, may agree at the two fixed points but will differ along their scales if these scales are uniform. To overcome the dilemma we imagine a perfect gas thermometer not unlike Galileo's instrument but with refinements, and establish its temperature scale. The properties of hydrogen are similar to those of the ideal gas, at least at ordinary temperatures, and it is not difficult to make the small corrections to temperatures obtained with a hydrogen thermometer which will bring them in agreement with the ideal

scale. Liquid thermometers can then be calibrated by comparison with the hydrogen thermometer.

The conception of absolute temperature, and the absolute temperature scale, arose not only from the study of the gas thermometer, but also from thermodynamics and a consideration of the Carnot cycle for an ideal heat engine. This temperature scale will be discussed later in the chapter.

The concept of temperature has thus developed from an arbitrary, qualitative concept to a definite and quantitative concept. Now that science possessed a means for measuring temperatures with accuracy, the theory of heat was in a position to advance. This advance leads not only to the realization that heat is energy, but also to the knowledge that temperature itself is a measure of the kinetic energy of atoms and molecules in solids, liquids or gases.

Heat had been regarded as an indestructible fluid called caloric, which could flow from one body to another. It was in the closing years of the eighteenth century that Black, in Glasgow, first made clear the difference between temperature and quantity of heat. His method was experimental. He noticed the great quantity of heat which must be applied to a piece of ice in order to melt it, although the temperature of the mixture did not rise until the ice was mostly melted. Black imagined that caloric was combined in some way in the ice and became latent in the water when the ice melted. The term latent heat has survived, but when used today it has a different meaning than that given it by Black. He also seems to have had clearly in mind the idea of thermal capacity and specific heat, for he noticed that a given amount of heat would raise a piece of metal to a higher temperature than it could raise the same mass of water. As his definition of heat quantity he used the amount of heat which would raise water from one temperature to another, a definition closely allied to that used today: The calorie is the amount of heat required to raise one gram of water through a range of one Centigrade degree. Black also used the idea of latent heat in discussing

the evaporation of water at constant temperature. His work helped pave the way for the modern science of calorimetry.

A spectacular line of development was soon to result in the complete overthrow of the concept of caloric and its replacement by the energy concept as embodied in thermodynamics. And, as is generally the case, the first definite advance resulted from an experiment. Several writers had already mentioned the idea that heat might be a form of motion, but their suggestions may be compared to the atomic theory of Democritus, who talked about atoms but did not establish the kinetic theory of gases.

The fact that heat can be developed in a body without being conducted in from a hotter body was noted by Count Rumford in Munich in the year 1797.

Rumford was American by birth (witness the popularity of the Rumford stove in rural New England) but later became a resident of Europe. He noticed that in the boring of cannon large amounts of heat were developed, especially if a blunt tool were used. He was perplexed by this observation and tried to discover the source of such large quantities of caloric. Experiments soon showed him that it could not come from the surroundings, nor from a change in thermal properties of the material before and after the boring process. Although the accuracy of his measurements leave much to be desired, he proved to his own satisfaction that heat and work are equivalent and that work can produce heat. He was the first to measure the mechanical equivalent of heat and found that one calorie was produced by the amount of work required to lift approximately seven hundred kilograms through a vertical distance of one meter.

But caloric was not yet ready to make its exit. Those who still regarded the older concept as the more reasonable explanation pointed to possible flaws in Rumford's experimental technique, and in his reasoning. One of the few who were at least partially convinced was Faraday's famous teacher, Sir Humphrey Davy, who attempted to determine

the source of the heat which is generated by friction. He tried the experiment of rubbing pieces of ice together under conditions such that any flow of heat would be away from the ice, not from the surroundings to the ice. Nevertheless the ice melted, and the conclusion was inescapable that heat had been produced by friction.

The experiment of Davy confirmed the observations of Rumford, and was even more conclusive. Rumford, Davy, and Young, proponent of the wave theory, believed that heat was some form of motion. Rumford's argument, though quite vague, insisted that since heat could not be matter or substance, it must be something else. The unlimited quantities of heat obtained in the boring process must result either from the creation of large amounts of the substance caloric (and the idea of the creation of matter was repulsive) or from the creation of motion, which was conceivable.

The implications of these experiments were realized by the German physician Mayer, who in 1842 made the first definite statement of the conservation law as applied to heat. Among other experiments, none of a very exact nature, he noticed that if a mass of cool metal is dropped from a considerable height into a vessel of water, the temperature of the water will be raised above the original temperature of either water or metal. He also found that the temperature of water could be raised by shaking it vigorously. He realized that heat was developed by the kinetic energy of the falling weight or the work done in shaking the water. Mayer measured the mechanical equivalent of heat and also the specific heat of air, though the accuracy of his experiments was not great. Although Rumford had become convinced that heat and work are in some way equivalent, and had attempted a statement of the conservation law, Mayer stated definitely that heat as well as mechanical work should be included in the conservation of energy. He believed that the work of Davy mentioned above was clear proof, supported by his own observations, and is often referred to as the discoverer of the principle that heat is

a form of energy. A few years previously the French engineer Seguin had made the remark that work can become heat; it was obvious to Mayer that heat can become work, and that in fact the two are different aspects of the same thing.

Things were in this somewhat unsettled state when Joule, in England, saw the experimental problem. Joule was born in 1818 and became interested in experimental science when still quite young, performing experiments in electricity and chemistry. It may be that his experiments in these fields suggested to him the idea that heat and energy are related. Heat and electricity are developed when metals are immersed in acids. Electricity can do work, and so can heat. Was there not some great principle which would include all these separate things?

During the years immediately preceding 1850, Joule measured the mechanical equivalent of heat in many ways. Indeed the symbol J which is now used to denote the amount of work or mechanical energy needed to produce one calorie of heat is taken from Joule's name. We also have a physical unit of energy called the joule.

By sending an electric current through a coil immersed in water Joule was able to measure the amount of electrical energy needed to produce one calorie. He also measured the mechanical equivalent directly by stirring water and noting the rise in temperature; the apparatus was not unlike a modern ice cream freezer. Paddles were rotated in the water, activated by ropes attached to falling weights which could be raised and lowered as many times as was necessary to produce the desired temperature change in the water. It was a simple matter to compute the work done by the falling weights by noting their mass and the distance through which they fell. A similar experiment is often assigned in college physics classes today. He also performed experiments in which heat is produced by friction.

Joule's value for the mechanical equivalent was 427 kilogram-meters of work, this being the amount needed to pro-

duce one calorie of heat. Because of the accuracy of his work, far exceeding that of any previous experiment in the field, he is considered to have established the first law of thermodynamics on a firm experimental foundation and to have proved beyond doubt that heat belongs in the category of energy, a category which today includes everything known to man, whether heat, light, motion, or matter.

The realization that heat and energy are equivalent, and that when one is changed into the other the relative amounts of each are always exactly the same, left no room for caloric; this knowledge has also had important results in the field of calorimetry. In experiments on the transfer of heat, early workers might have taken precautions to prevent the loss of caloric. But with a knowledge of just what is lost, and how, greater precautions may be taken with resulting increase in experimental accuracy. The concepts of heat of vaporization and heat of fusion take on new meaning; the concept of caloric in the latent state was hardly sufficient to furnish knowledge of the physical states of solids, liquids, and gases, or the differences between these states. It became possible to study the flow of heat energy along a metal bar and to determine what process is responsible for the flow. The similarity between heat conductivity and electrical conductivity could never have been understood on the basis of caloric.

The above knowledge, and the certainty that the electrical equivalent is numerically the same as the mechanical equivalent, is of great importance in this industrial age. Engineers are able to follow the flow of energy from fuel to boiler, or from the waterfall to generators, motors, and finally production machines. Where every step in the process is understood, improvements in the efficiency of each step can be intelligently attempted.

The first principle of thermodynamics states that when heat is given to a volume of gas the gas will become hotter and will also expand if it is allowed to do so. The amount of heat added is exactly equal to the sum of the increased heat energy

of the gas and the work done in the expansion, all quantities being measured in the same units of heat or energy. The validity of this law, and indeed its very formulation, could not have been apparent before the work of Mayer and Joule.

It is this principle of thermodynamics which forbids perpetual motion of the kind that would create energy from nothing. No energy can be produced without using at least as much energy in another form. If friction could be eliminated entirely a machine could be constructed which would run indefinitely, though it could not supply any power.

Another sort of perpetual motion, allowed by the first principle but never observed, is forbidden by the second principle of thermodynamics.

A discussion of the second principle must begin with the work of Sadi Carnot, in France, who studied the action of heat engines. He compared the flow of heat through a heat engine to the flow of water over a waterfall. Water can do work only if it is allowed to fall: there must be a difference in level, a difference in potential energy which can be converted into other forms of energy. Water imprisoned in a mountain lake is powerless to generate electricity, while vast industries use the power generated at Niagara. It is the falling of the water that does the work. In a heat engine, heat must flow into the engine and out again; hot steam gives some of its energy to the piston or turbine blades and emerges with less energy, often condensed into water. If the steam emerged at its initial temperature the pressure would be the same on both sides of the piston or turbine rotor and no work would be done.

Carnot recognized the impossibility of the flow of heat from one place to another unless impelled by a difference of temperature, just as undisturbed water will not move unless it can flow to a lower level. The first formulation of the second principle was made by Carnot in 1824 and the law is often referred to as Carnot's principle. We have retained the law even though Carnot originally thought in terms of caloric—

the establishment of the mechanical theory of heat lagged his work by some twenty years. If it seems surprising that Carnot could state an important principle in the theory of heat without an understanding of the true nature of heat energy, we may recall that electricity was used, and important electrical principles correctly stated, long before anyone had more than an inkling of its nature.

Carnot invented what is known as the Carnot cycle, an imaginary process conducted by means of an imaginary engine. Though ideal, the cycle gives important information concerning the operation and efficiency of all real heat engines.

Imagine a heat engine consisting of a cylinder and piston whose walls, except for the bottom, consist of material such as ideal asbestos through which no heat can flow. The cylinder contains gas, and may be placed on one of three stands: the heater, a reservoir of heat energy at a high temperature; an insulating stand; the cooler or condenser, a reservoir of heat energy at a low temperature. Heater and cooler may consist of large blocks of copper, each maintained at constant temperature. The volume and pressure of the gas depend on the position of the piston, the temperature of the gas, and the weight placed upon the piston.

Suppose that the cylinder has been resting on the cooler for a long time, so that temperature equilibrium has been established. The cylinder is transferred to the nonconducting stand and weights are added to the piston so that the gas is compressed and thereby raised in temperature since the gas is perfectly insulated: no heat energy can enter or leave the gas by conduction. When the temperature of the gas reaches that of the heater, the cylinder is transferred and the piston is unloaded so that the gas expands at constant temperature, heat energy now entering from the heater to counteract the cooling which would otherwise result from the expansion. Once again placed on the nonconducting table, the piston is further unloaded and the gas is cooled by expansion. The

final stage takes place on the cooler, where the piston is loaded so that the gas returns to its original pressure and volume, in which process the heat which would result from compression is transferred to the cooler. In the complete cycle, heat has been transferred from the hot reservoir to the cold reservoir, and mechanical work has been done by the piston.

By a consideration of this cycle Carnot showed that the efficiency of any heat engine can never exceed a definite quantity which is considerably less than one hundred percent, and that no real heat engine can have an efficiency as high as that of his ideal engine. The maximum ideal efficiency depends on the temperatures of the heater and the cooler, a fact which indicates one way in which the efficiency of real engines may be increased in practice.

Implicit in the Carnot cycle is the fact that heat will not of itself flow uphill, from a lower temperature to a higher temperature. Heat could be transferred from cooler to heater, but work would have to be done on the gas by operating the piston mechanically. For instance, the gas might be expanded at the temperature of the cooler, in which case it absorbs energy; it could then be compressed on the insulating stand to a high temperature, and finally give heat energy to the heater. But work is done to achieve this result; and if left to itself, heat energy will only flow downhill.

In 1850 Clausius stated the principle in the explicit form that heat will not pass spontaneously from one body to another that is warmer than itself. According to another statement, no change will occur in a closed system of bodies in which one of the bodies loses heat while another at the same or higher temperature gains potential energy.

It will be seen that the second principle of thermodynamics forbids a sort of perpetual motion which would be allowed by the first principle. The oceans contain an enormous supply of potential heat energy, but there is no great reservoir of water at a lower temperature to which heat energy can flow; the

Arctic is too far away. Attempts to utilize the difference in temperature at the surface of the ocean and at great depths have met with partial success, though in this case a different process is involved: at the surface, the heat energy of the ocean is of no practical use for the operation of heat engines. The energy is there, and its use would not involve the creation of energy, but its use is impossible.

The second law has been called the principle of the availability of energy. Heat energy is not available for any practical use unless a difference in temperature is also present.

It is this law which has been invoked to prove that the universe is running down, that hot bodies are cooling and cold bodies becoming warmer until everything, stars, planets, and even interstellar space will be at the same temperature, and life will be impossible. If such is to be our fate, it will at least be postponed for many millenniums.

Carnot's work was greatly aided by the support of the young William Thomson, later Lord Kelvin, who was among the first to see its importance, and who later was to bring the Carnot cycle under the mantle of the new theory of heat as energy, not caloric.

The absolute temperature scale was introduced by Thomson. Gas contained in a closed vessel decreases in pressure when cooled in such a way that at a temperature of 273 degrees below zero on the Centigrade scale it should have no pressure at all, and presumably no heat energy, since the temperature of a gas depends on the kinetic or heat energy possessed by its molecules. Similarly, the amount of work obtainable from one cycle of operation of a Carnot engine depends on the temperature of the heater as well as the difference in temperature between heater and cooler and, at minus 273° C., no work can be obtained from such an engine. Absolute temperatures agree, whether defined on the basis of gaseous expansion or on the Carnot cycle, but the latter has the advantage that the definition of absolute temperature is independent of the substance used in the definition. The freez-

ing point of water, on the absolute or Kelvin scale, is 273 degrees above absolute zero; the size of the absolute degree is the same as the Centigrade degree.

The theories of Carnot, Clausius, and Kelvin have received more than adequate confirmation during the development of the steam engine by Papin, Newcomen, Watt and many others. The two principles of thermodynamics are now included among the important generalizations of modern physical science.

Chapter 5

MOLECULES

HISTORY CONTAINS many instances in which scientists have laid the foundations for important advances in knowledge without themselves recognizing the significance of their discoveries. The above statement has been especially true in the realm of experimental science, where the scientist frequently seeks an explanation of his new results on the basis of theories which he regards as established. It is often left for others to prove that the theory, not the experimental result, needs to be refined or replaced. Occasionally the observer is prejudiced but more often it is true that the time is not quite ripe for new ideas, ideas, in fact, which may have been quite unnecessary and even unforeseeable before the performance of the experiment.

The first experiments concerning the nature and behavior of gases did not lead at once to the modern concept of a gas as consisting of minute atoms and molecules, bounding hither and thither, a concept which has formed the basis of the modern kinetic theory of gases. The earliest experiments performed on the properties of gases, and having any considerable accuracy, were those of Robert Boyle, the Oxford physicist, who about 1660 published the results of his experiments on the elasticity of air.

Boyle arranged a tube shaped like the letter U, one end of which was closed. By pouring mercury into the open end air was compressed in the closed portion of the tube; it thus be-

came possible to study the changing relations between pressure and volume of the air as more mercury was added. He found that for a given mass of air, volume and pressure were inversely proportional and their product was constant. This relation is known as Boyle's law; Boyle did not realize that his law is valid only so long as the temperature remains constant, but in his experiments the variation of temperature may have been so small as to introduce only minor errors. The fact that the law is strictly true only for the ideal or perfect gas, to which hydrogen and helium at ordinary temperatures are good approximations, does not detract from its usefulness. The compressibility of air was also studied by Mariotte, but Boyle was the pioneer. Galileo may have known something of the compressibility of air from his work on the air thermometer, and it had been generally known that elastic bodies contract under pressure. Boyle's achievement lay in the care with which his experiments were performed.

Boyle's purely experimental result was obtained without any good idea of the nature of air. At the time, two points of view were possible: If a person were influenced by the ideas of the early atomists he might imagine air to consist of particles of some sort, though what these particles were like, how large they were, or how they behaved were open questions. If on the other hand one were not inclined to accept the crude theories concerning the supposed atomic constitution of matter, air and other gases might be supposed to consist of continuous material having elastic properties. Luckily, for the success of Boyle's measurements no theory was necessary. In this instance, as is so often the case, theory waited upon experiment.

The way in which the pressure or volume of a gas changes with change in temperature was studied to some extent by the French physicist Amontons, who about 1700 was experimenting with the air thermometer. Later Charles, also in France, studied the expansion of gases with change in temperature, and in 1802 Gay-Lussac published the results of still

Courtesy R. C. Williams and R. W. Wyckoff

enza virus (the big spheres) magnified about 60,000 diameters by the electron microscope.

more accurate observations. Since the expansion of a gas with rise in temperature is nearly the same for all gases, the concept of absolute temperature was implicit in the work of Charles and Gay-Lussac; however, absolute temperature became an explicit concept at a considerably later date. As now formulated, the law of Charles and Gay-Lussac states that the pressure of a gas, maintained at constant volume, is proportional to the absolute temperature; or that the volume of a gas, maintained at constant pressure, is proportional to the absolute temperature. It is assumed of course that the gas is not too close to conditions which will result in liquefaction, in which case its properties depart very considerably from those of the ideal gas.

These workers are not regarded as founders of the kinetic theory of gases, even though their discoveries were to assist in its establishment. Whether or not they could foresee the ultimate importance of their observations, they proceeded to find out as much as possible about the nature of gases. Like Tycho Brahe in the field of astronomy, they recorded facts which might prove useful to later scientists.

An experimental foundation had thus been laid, and facts presented to the scientific world for explanation. It was natural that at this stage someone should attempt to explain the experimental relations between pressure, volume, and temperature on the basis of reasonable assumptions concerning the nature of a gas. This attempt was made by Bernoulli shortly after 1730. He accepted the idea that gases consist of small discrete particles, continually in motion. Although he had no clear idea as to what these particles might be, how they moved, or what laws were obeyed when one particle collided with another, he was able to show by mathematical reasoning that gas pressure can be explained as the result of the impact of particles against a surface, and that the laws of Boyle and Charles must result from his assumptions. Bernoulli is often called the founder of the kinetic theory; in any event, he was the first to present a truly scientific argument

for the existence of the small particles which were supposed to make up a gas, and for their constant motion. He had no definite idea concerning the nature of these particles, nor had he any conception of the difference between the two fundamental kinds of particles, atoms and molecules; but his work was in every way scientific as contrasted with the atomic theory of Democritus, who merely conjectured the existence of fundamental particles. Bernoulli had the tremendous advantage of possessing experimental facts upon which to build. He may have obtained a suggestion from the writings of Democritus, and we may believe that his work was accepted the more readily because of the persistence in Greek literature, and later, of the ideas of the atomists, ideas which were accepted in part even by the great scientist Newton.

It was chemistry, rather than physics, which first provided a definite concept of the atom, and later the molecule.

Since air and other gases were supposed to consist of small particles in constant motion, it became necessary to find out more about these particles. In the years immediately following the work of Bernoulli, the only available way to study the nature and behavior of these particles was to examine the chemical combination of substances presumably made of them. At this time chemistry as well as physics was in the process of becoming an exact science. The use of the balance in accurate weighing was more and more regarded as essential in chemical work, and was establishing the hitherto unknown fact that chemical compounds were not the same as physical mixtures. In a mixture the components may be present in any desired proportions, whereas in a chemical compound the relative amounts of the components are always the same. Salt and sand may be mixed in any manner desired, but when sodium and chlorine react to form sodium chloride, then if more than the right amount of either is present the excess will not enter into combination. It had also become apparent, principally through the work of Lavoisier with the chemical balance, that in a chemical reaction matter is neither

created nor destroyed; the weight of matter entering into a chemical reaction is always equal to the weight of the products of the reaction. Such were the foundations upon which Dalton was to build.

John Dalton lived from 1766 to 1844. He has been generally known as a chemist, but his work has had important implications for the science of physics as well. Experiments on the solubility of gases in water turned his mind to the possibility that the particles of which gases were supposed to consist might be of various sizes and weights, and might be present in equal volumes of the different gases in varying amounts. In order to test such points he studied the facts of chemical combination.

In a chemical compound the relative weights of the different components are always the same. This fact alone would indicate that the components of a compound might consist of discrete units which combine in simple ratios. Dalton's examination of chemical compounds enabled him to enunciate the law of multiple proportions, in connection with which his name is often mentioned in modern chemistry. Although he did not at first recognize the difference between atoms and molecules, and was ignorant of the fact that two separate types of particles must be considered, he made the following significant statement: If carbon, for example, unites chemically with sulphur, or with oxygen, then the weights of oxygen and of sulphur which separately will unite with the same weight of carbon are related to each other as are two simple whole numbers. This announcement occurred in the year 1808.

The chemical reaction of gases was studied by the French scientist Gay-Lussac, a contemporary of Dalton, who had also examined the thermal expansion of gases. At this time the laws of Boyle and of Charles (and Gay-Lussac) were well established, and were helpful in the interpretation of experiments on gaseous reaction. Of especial interest were the volumes of the gases entering the reaction as well as those resulting from the reaction. Gay-Lussac found that if all

gasses concerned were considered at the same temperature and pressure, then two liters of hydrogen would unite with one liter of oxygen to produce two liters of steam. For other gases the proportions might be different but in every case the volumes of the various gases were related to each other as are simple integers.

These facts indicated that under standard conditions all gases might contain the same number of particles, or atoms, as they were called, in each unit of volume. Though the above statement is essentially correct, one very important detail is omitted: no distinction is made between atoms and molecules. This omission in fact led to contradictions in Dalton's explanation of the manner in which gases enter into chemical combination. It would be most difficult to arrive at a consistent system of atomic weights unless molecules are distinguished from atoms, since one, two, three or more atoms may combine to form a molecule. Besides, if equal volumes of gas at the same temperature and pressure contain the same number of atoms, Dalton believed that one liter of hydrogen should combine with one of oxygen to produce one liter of steam, one atom of each component contributing to the function of one atom of steam.

The differentiation between atoms and molecules was left for Avogadro, who in 1811 showed that all difficulties would disappear if it were assumed that the atom is the ultimate particle, and that atoms can combine into molecules. The number of molecules, not atoms, should be the same in equal volumes of gases at the same temperature and pressure. Avogadro's law, of which the last sentence is a statement, is one of the more useful and fundamental of the scientific generalizations which contemporary science has inherited. After the success of Avogadro, Dalton's explanations became completely applicable to the facts of chemical combination, and he could proceed to a determination of the relative atomic weights of the various elements. Measurement of atomic

weights was later carried on by Berzelius and others with great success.

It soon became apparent that regularities exist in the system of atomic weights. If the elements are arranged in order of increasing atomic weight, certain elements have properties similar to those of elements higher or lower in the list. The large number of such similarities led, through the work of several scientists, to the establishment of the periodic table of the elements, as given about 1870 by Mendeléjeff. Modern versions of this table constitute one of the most useful tools of the chemist; the elements are arranged in a rectangular array, the atomic weights increasing from left to right in each horizontal row, and from row to row downward. The elements in each vertical column are chemically related and have similar properties. Gaps in this table have led to the search for and the discovery of new elements. However, as new elements were found and atomic weights in general measured with increased accuracy, it became evident that the periodic table could not be in its final form, or else its significance had been overestimated: a few elements would not fit correctly into the scheme. It will appear later that these discrepancies were only apparent, and that their removal has been one of the triumphs of modern science.

Chemistry has thus been principally responsible for knowledge concerning the fundamental difference between atoms and molecules. It is necessary at this point to mention a hypothesis of Prout, presented while Dalton and Avogadro were making their discoveries, to the effect that all elements might be built up from a single element, possibly hydrogen. This hypothesis was suggested by the fact that atomic weights of various elements were approximately equal to multiples of the atomic weight of hydrogen. More accurate measurements of atomic weights made this assumption untenable for many years; but modern science has returned to Prout's hypothesis, armed this time with experimental evidence adequate to prove its essential correctness. The fundamental element is not

hydrogen; but the hydrogen nucleus, or proton, is one of the very few elemental components of all the elements, from the lightest to the heaviest.

Now that the existence of atoms and molecules had been established, and their difference recognized, it was possible for the kinetic theory to develop. An important discovery, made soon after the work of Dalton and Avogadro, should have given the theory a great impetus. The situation is instructive in showing how scientists sometimes allow important facts, which might lead them into new realms of achievement, to lie dormant for years because of their inability to appreciate the significance of new experimental results. Brownian motion, discovered in 1827 and now regarded as one of the best proofs of the molecular theory, had to wait for a correct explanation until 1879, when the molecular theory had been brought to maturity along other lines.

In 1827, Robert Brown in England was performing experiments in botany. While engaged in watching minute forms of plant life under a microscope he observed that the smallest objects appeared to be in continual motion, not a motion from place to place but one of violent agitation. He ascertained that these particles were not alive, but were in fact bits of dust or vegetable matter. He recorded the observation, although any sort of reasonable explanation was beyond him. The explanation was given in 1879 by Ramsay, who realized that Brownian motion of small particles in a liquid or gas is a result of molecular bombardment. The subject has been treated by many, notably Einstein, who has derived important results from measurements made on Brownian motion.

A simple analogy will illustrate the cause of the observed motion. Imagine that someone is standing near a lake, admiring the scenery. The surface of the water is very smooth, there is hardly a ripple. At last his eyes come to rest on an object at some distance from the shore, an object that is undergoing considerable agitation, though never moving very far in any one direction. Expecting to see a small animal in

distress, he reaches for a telescope and finds that the object is apparently a piece of bread. A companion wonders what would happen if fish were nibbling at the bread, attacking it from all sides, each trying to get the largest bite. If more fish were on one side than on the other, the bread would be pushed to one side a little, and then in another direction. The companion has unwittingly played the part of those who later were to explain Brown's discovery, though he possessed one advantage: he could row out and see the fish. No one can see a molecule.

Anyone possessing a powerful microscope can see what Brown saw, either by looking at a liquid containing fine particles of matter or by watching smoke particles suspended in air. In either case strong illumination is essential. It seems strange that the true explanation escaped the scientific world for more than fifty years. Bernoulli had shown that the assumption that gases consist of particles in continuous and rapid motion was not absurd, while Dalton and Avogadro had furnished evidence for the reality of atoms and molecules. Today the Brownian motion is regarded as one of the mainstays of the kinetic theory, possibly the most directly observable evidence of the motion of molecules in gases and liquids. The development of the kinetic theory would have been more rapid if the significance of Brown's discovery had been recognized earlier.

The concept of molecular motion was gaining acceptance in many quarters, partly because of the simultaneous development of the mechanical theory of heat. The relation of heat to other forms of energy was being established by Rumford, Joule, Clausius and others, and the idea that the heat energy of a gas might be nothing else than the actual kinetic energy of the molecules would seem to be a natural conclusion. The next advance was made by Joule, who is not often thought of as a contributor to the kinetic theory. By considering, as Bernoulli had done, that gases consist of molecules in continual and rapid motion, and that gas pressure is caused by

molecular impacts on the walls of the containing vessel, he was able by means of a dynamical argument to calculate the average velocity which molecules must have in order to produce the observed pressure. His value for the average speed of hydrogen molecules at atmospheric pressure and room temperature, slightly over six thousand feet per second, is of the same order of magnitude as the value accepted today, a surprisingly accurate result for such pioneer work. His result was obtained in 1848.

Clausius, about ten years later, continued the work of Joule on the kinetic theory. He was also deeply interested in the theory of heat. Clausius extended the arguments and discussed the case of elastic spheres moving about and colliding with each other and with the walls of the container. On the assumption that gas molecules could be considered to resemble elastic spheres, he had considerable success in deriving the gas laws, which themselves rested on a firm experimental foundation. Bernoulli's earlier work was thus confirmed.

If gas pressure is the result of molecular impact, then the pressure will be greater when more molecules are hitting the surface at which pressure is measured. Thus Boyle's law is verified, for as the volume of a gas is decreased the density of molecules increases and more will strike the surface, producing an increase in pressure. Further, if the heat energy of a gas, of which the temperature is a measure, is essentially the kinetic energy of the molecules, these molecules must move faster when the temperature is higher, resulting in the increased pressure demanded by the law of Charles and Gay-Lussac. Clausius also achieved success in the explanation of facts concerning the diffusion of gases.

During the years immediately following the work of Clausius, James Clerk Maxwell lent his genius to the problem. He is principally remembered for his brilliant electromagnetic theory of light, but almost as much for contributions to the kinetic theory. Clausius had considered that all molecules in a sample of gas moved with the same velocity, which

he called the average velocity. It was clear that the assumption of equal velocity was at best improbable, and Maxwell set about making the proper corrections.

An analogy will indicate the nature of Maxwell's contribution. Suppose someone is trying to see how far he can throw a stone. He throws the same stone repeatedly, trying to use the same effort each time, and notices that the stone travels different distances. After many throws it becomes apparent that there is a certain distance at which the stone most often falls, though a few times it moves farther, and a few times not so far. Occasionally the deviation is large, but more often the stone falls quite near the average position. Thus the thrower has found his average range. He could have saved himself considerable trouble if he had made a very few throws, then consulted the theory of errors or of probability, to find out what the chances were of throwing the stone exactly the average distance, or a greater distance, or a much greater distance, always using the same effort. Ten thousand throws were needless—the mathematicians have it all worked out.

Maxwell applied the theory of probability to the kinetic theory. He felt that it was sufficiently correct to speak of the average velocity of gas molecules, but he wished to find out what would happen if the laws were derived from the more correct hypothesis that molecular velocities are distributed around the average velocity in a manner given by the theory of probability. He derived what is called Maxwell's distribution of velocities, which applies to the velocity of gas molecules as well as other problems, notably the distribution in velocity of electrons emitted from hot filaments in lamp bulbs and vacuum tubes. His law of the distribution of velocities has been amply verified, both for gas molecules and for thermally emitted electrons.

Maxwell also extended the kinetic theory in other ways, and made predictions concerning the viscosity of gases. In this connection he introduced the concept of intermolecular repulsive forces. Together with Boltzmann he established the law

of the equipartition of energy. The law states that with every so-called degree of freedom, one of the many possible modes of motion of a particle, there is associated a definite amount of kinetic energy, which in an ideal gas depends only on the temperature. In a gas there are many particles; the total number of degrees of freedom is the product of the number of molecules and the number of degrees of freedom of each particle. The heat energy of the gas depends, not on the nature of the molecules, but on the total number of degrees of freedom and the temperature.

Molecules of the imaginary perfect gas do not occupy any space, nor do they exert forces on each other except those resulting from impact. Although Maxwell departed from the perfect gas in his study of viscosity, his ideal gas was supposed to consist of tiny, perfectly elastic spheres which could bounce off of one another with no energy loss whatever. The principal difficulty with these imaginary bodies is that a theory based on their assumption will not describe with accuracy the behavior of real gases.

In 1873 Van der Waals made the great advance of including in the theory the actual sizes of molecules as well as intermolecular forces. The finite size of molecules decreases the space at the disposal of each molecule, while forces between molecules alter the gas pressure. The equation of Van der Waals, called the equation of state for real gases, comes very close to describing the behavior of actual gases when volume, pressure, and temperature are changed. The laws of Boyle, Charles, and Gay-Lussac combine into the equation of state for ideal gases. The state of a gas is simply its condition of temperature and pressure, and the equation relates these quantities to volume and mass.

The kinetic theory was achieving considerable success and was soon to have more arguments in its favor. In 1879 Ramsay brought forward an explanation of Brownian motion, while in 1887 Van t'Hoff showed that his studies of osmotic pressure indicated that molecules in liquids obeyed kinetic

theory predictions originally made for the behavior of gas molecules, especially if the molecules under consideration were those present in a dilute solution.

In experiments made near the beginning of the present century, Perrin studied the behavior of small particles suspended in liquids and produced strong evidence for the correctness of the kinetic theory. He studied the distribution of particles through the liquid and found a situation not unlike that of the earth's atmosphere. If it were not for the kinetic energy of the molecules, the air would all settle on the surface of the earth, drawn downward by gravity. It is possible to compute how gravitational forces and the kinetic energy of the molecules will to a degree balance each other, whether in the atmosphere or in a liquid suspension. In either case, the information desired is the resulting distribution of particles at different altitudes or depths, and an explanation of the observed distribution. The advantage of Perrin's method is apparent when one considers the relative ease of counting particles through a microscope in the laboratory, or climbing high mountains. Barometric observations made at different altitudes confirm the distribution law and furnish additional support for the kinetic theory.

In one of its branches the kinetic theory approaches parts of thermodynamics. Statistical mechanics, an outgrowth of kinetic theory, is concerned with many of the problems formerly approached solely through the second law.

According to the second principle of thermodynamics, the trend in physical occurrences is toward a condition of equilibrium. However salt first came to exist in the ocean, the distribution of salt will always become more uniform as time goes on. The predictions of statistical mechanics agree in general with those of thermodynamics; statistical mechanics considers each molecule of salt, not individually but statistically. It is conceivable that, very rarely, the salt molecules will by chance have such motions that they will accumulate in one locality, leaving oceans of fresh water. Of course the

nearly uniform distribution is by far the most probable one, but it may not be as inevitable as the second law would lead us to believe. It is quite possible to compute the probability that the shuffling of a deck of cards will place them in order according to number and suit; the probability is small, which means that very many repeated shufflings will be required before the desired result is produced. But it can be done. Thermodynamics, if applicable to the shuffling of cards, would say that no alteration in the trend towards more and more random distribution is possible, or will ever become so.

Chapter 6

MAGNETISM AND ELECTRICITY

THE KNOWLEDGE that a relation exists between magnetism and electricity, both known independently for centuries, is just over a hundred years old. Without this fundamental knowledge, the triumphs of modern electrical engineering and communications would not have become possible.

The life of Michael Faraday, famous pioneer in the field of electromagnetism, should be of interest to those psychologists who hold that the average man uses but a small fraction of his latent mentality. Faraday displayed a most extraordinary intellectual activity. His was a well ordered life, in which faith, love of nature, beauty, and a philosophy of happiness played an important part. But he was so diligent in the pursuit of truth that eventually his memory was impaired; in later life he would find himself performing experiments he had only recently brought to a successful conclusion.

Volumes have been written about the life and work of Faraday, emphasizing our indebtedness to him for many things that have enhanced modern civilized life. The electric motor with its many uses, the dynamo and the transformer are traceable to his laboratory. It is not alone for his discoveries that scientists regard him with reverence; the discoveries would have been made by others, and indeed one made by Joseph Henry, in America, preceded a similar one made by Faraday, though delayed publication gave Faraday the priority. His immense intellectual drive undoubtedly pro-

duced more discoveries sooner than would have been the case had they been left for others. He is remembered as a clever experimenter with a keen mind, who thought along broad lines and always tested his theories with extreme care in the laboratory, guided by his belief in the inherent simplicity and unity of nature.

A better understanding of his achievements can be gained by an examination of the state of the scientific world he was to enter. At the beginning of the nineteenth century experiments in the science of electrostatics had provided some information regarding the behavior of electricity, without however furnishing any definite conception of its nature. Von Guericke had constructed his electrical machine, in which electricity was produced by the friction of the hand on a ball of sulphur, essentially the same mechanism as that of Thales over a thousand years earlier, but more convenient. Gray had recently found that the electricity produced by friction could be conducted from one place to another by means of metal wires. Further, a study of the attraction and repulsion of electrified bodies had shown the existence of two different kinds of electricity, identified in quite arbitrary fashion as positive and negative; it was known that two electrified bodies would attract or repel each other, depending on whether they possessed opposite or the same kind of electric charge. Observations made in the study of electrostatic induction led to a discussion as to whether there were in fact two electrical "fluids," or only one whose presence or absence would appear as an electric charge of one sign or the other.

Many experiments in electrostatics are easy to perform, in fact a few have been performed, knowingly or unknowingly, by nearly everyone. The spark obtained after brushing or combing the hair on a cold dry day, or walking across a rug, is evidence of electrification by friction. Friction of the arm on a piece of writing paper will often cause electrical attraction to the table top. Other experiments, though just as simple, require more apparatus.

Imagine a metal sphere, supported by a glass rod for purposes of insulation. An electrical charge can be given to the sphere in many ways, the simplest of which is to touch it with a piece of wax or hard rubber which has been rubbed with woolen cloth. Imagine also a second body of metal, preferably egg-shaped, and also mounted on a glass rod.

If the two metal bodies are allowed to touch, electric charge originally on the sphere will distribute itself over both bodies. But instead of allowing them to touch, they may be placed close together, though not close enough for a spark to pass between them. Suppose that the original charge on the sphere was positive. It is then found that the portion of the egg nearest the sphere shows a negative charge, and the portion farthest from the sphere a positive charge. If the sphere is removed, the egg is left without a charge. But instead of removing the sphere, let the egg be touched with the finger or a metal object held in the hand. Then when the sphere is removed the egg will be found to possess a negative charge—it has been charged without touching it to the charged sphere, by induction.

The proximity of the charged sphere causes a separation of the charges originally present in equal quantities in the uncharged egg. Speculation was rife as to whether both kinds of charges were mobile, or only one, in which case a lack of the mobile charge appears as a charge of the opposite sign. Either assumption is able to explain the experiment. Modern evidence indicates that only negative charges are mobile in conductors, the positive charges being intimately associated with the nuclei of atoms. Negative electrons are attracted toward the positive sphere, leaving a decreased number on the far end of the egg, which then possesses a residual positive charge. These charges recombine if the sphere is removed before the egg is touched; but in the above experiment, negative charges were attracted through the hand to the egg because of the action of the charged sphere, and the egg was left with an excess of negative charge.

Coulomb had studied the laws of magnetic and electrical attraction and by means of his torsion balance had proved that in both cases the law of force is an inverse-square law, as indeed is the law of gravitation. Cavendish obtained the same result, using however not electrical forces but a different experimental method with greatly refined accuracy. The mathematical theory of electrostatics was being developed, and a new field, that of current electricity, was soon to open up.

In 1790 Galvani had been engaged in dissecting a frog. His knife touched by chance a piece of metal also in contact with the frog's leg and the muscles of the leg unexpectedly contracted. No doubt someone had previously come in contact with a charged body and noticed the muscular contraction caused by electric shock, but in any case the contraction of the frog's muscle was soon recognized as being caused by electrical action. The novelty consisted in the discovery that electricity is produced by the action of metal and moist animal tissue in contact.

The accidental but none the less fruitful discovery of galvanic action, as it was called, soon led to new advances. A study of the effect by Volta resulted in the construction of the first electric cell, or galvanic battery. The original voltaic pile consisted of layers of metal discs, two different metals being used with moist paper between alternate discs. Later a cell was constructed in which two plates of different metals were immersed in a dilute solution of acid in water. Use of such wet cells led to the discovery that the currents produced, when caused to flow through a conducting liquid, were able to cause the decomposition of water into oxygen and hydrogen. Sir Humphrey Davy, who was to become young Faraday's scientific master, was greatly interested in these new effects.

Until the beginning of the last century the study of magnetism and that of electricity, whether static or current, had progressed separately. It is natural to suppose that someone must have suspected a relation between electricity and magnetism. The fact that both obeyed the inverse square law of

Courtesy Robert Yarnall Richie and the Allis-Chalmers Co.

A modern transformer bank.

attraction and repulsion must have been suggestive. Men may speculate about many things and in many ways, but in science, at any rate, such speculations soon disappear unless they are verified by experiment. If an hypothesis is made and later verified, its author is honored for his insight; if the hypothesis is not borne out by the facts, then the author is generally regarded as having been misguided. It is often difficult to tell whether certain great scientific discoveries have been made by accident. A person who had believed in 1800 that there was a relation between electricity and magnetism would today be regarded as a prophet, a man of remarkable scientific insight. But if he had prophesied a relation between magnetism and gravitation, for which at the time he would have had as much reason, he would at present be called a misguided dreamer.

In any case, whether intentionally or not, a relation between electricity and magnetism appeared. In 1819 Oersted noticed that a magnetic needle was affected by a current of electricity. A compass needle on his laboratory table was deflected when current from a cell flowed through a wire near the needle. This discovery was the door to new achievements. It generally happens that when an epoch-making discovery is announced the entire scientific world pounces upon it, repeating the observation and trying to extend the field. And just as often it happens that of the entire army of scientists one or two will distinguish themselves and stand out above all the rest. This time the honor was to belong to Faraday.

After the announcement of Oersted's discovery, Ampère in 1820 succeeded in showing that one current could affect another; there was a mechanical force, not only between the wire and the magnet, but also between two wires in which electric currents were flowing. It was argued by some that the attraction might be a static force between charges, but Ampère was able to refute his critics by demonstrating that the force was one of attraction or repulsion depending on the direction in which the currents were flowing. Modern texts refer to Ampère's rule which gives the direction of magnetic forces

around a wire carrying a current. Ampère studied the new effects mathematically as well as experimentally, and derived a law which together with the discoveries of Faraday was to become the foundation of Maxwell's great electromagnetic theory.

Ampère visualized the effect of a permanent magnet as resulting from the action of many small magnetic particles within the magnet, and disagreed with many of his colleagues in assuming that each magnetic particle might really be a small electric circuit. He studied the magnetic action of currents in a closed circuit and compared such action to that of a system of permanent magnets. It is interesting to compare this early view with the modern one of electrons circulating in atoms and also with the still more recent idea that the spin possessed by electrons endows them with intrinsic magnetic properties.

Michael Faraday was born in England in 1791. Forced by the circumstances of his family to forego the advantages of a university education in order to earn his living, he was employed first as an errand boy, then as apprentice in a book bindery. At the bookshop he became interested in science by reading the books which passed through his hands. This interest came to fruition when he was able to attend lectures given by the well known chemist, Sir Humphrey Davy of the Royal Institution. Davy had contributed to the development of the mechanical theory of heat, and was the inventor of the miner's safety lamp. The boy Faraday was much impressed by the lectures; he listened attentively, took careful notes, and edited his notes with great care whenever he had the time to spare from his other duties. As evidence of his earnestness, he sent these notes to Davy, together with a request for employment in any capacity which would bring him closer to the science which fascinated him. Davy was impressed, and a few months later Faraday joined the staff of the Royal Institution as laboratory assistant, at the age of twenty-two.

In the same year, 1813, Faraday accompanied Davy as sec-

retary and assistant on a tour of scientific institutions and laboratories in many countries of Europe. This contact with the work of outstanding scientists presented an opportunity for the eager young man to learn much that would later be of use to him.

Faraday advanced rapidly in scientific knowledge and skill and in 1823 was elected a Fellow of the Royal Society. The following year saw his appointment as lecturer at the Royal Institution, and a year later he was made director of the laboratory. He soon gave up lecturing, as well as research of a commercial nature, both of which were quite remunerative, in order to have strength and energy for the work in pure science which attracted him, even though it offered him no reward other than the satisfaction attending good work well done. He probably did not know that it was to offer fame as well.

Faraday desired further insight into the mysteries of science, and evidence to support his belief in the essential unity of nature. He would have been astonished could he have foreseen the achievements to which his discoveries were to lead, both in pure science and in the many applications of modern industry. Possibly he did foresee a little, when he would remain alone in his garden, watching the last glow of sunset and thinking thoughts that were not expressed.

Here then was Faraday at the age of forty and in the fulness of his powers, famed of men but undesirous of their praise, with all the scientific resources of the day at his command, full of plans for finding the answers to perplexing questions and for verifying his fundamental beliefs. His firmest conviction was that of the unity and simplicity of nature: nature should appear simpler to us, more related in all its aspects and ruled by simpler and more fundamental principles, the more fully she is understood. Today scientists are still trying to find unifying principles which they feel must exist; whenever a principle or law of nature turns up which includes categories formerly believed to be distinct, the dis-

covery of the unifying principle is regarded as a significant advance.

Faraday commenced a series of experiments the reports of which he has called "Experimental Researches in Electricity." In line with his search for unity and simplicity, he was consciously looking for an inner relation between magnetism and electricity. Oersted and Ampère had shown that magnetism is related to current electricity, now Faraday wished to prove that one could be obtained from the other. He also had another aim. The contemporaneous conception of "action at a distance" as an explanation of the transmission of electric or magnetic forces was repugnant to him. He could not picture any process by which an occurrence at one place could produce action somewhere else, unless some physical connection existed between the two locations. He desired to demonstrate the connection between the magnet and the object attracted by it.

If the early entry in his record book indicates the first attempt to obtain electricity through the use of magnetism, his success was almost immediate. It is not certain just how much work he had already done along this line while concentrating on experiments of a different nature. As noted in the record, he constructed what turned out to be the first transformer, a simple ring of iron supporting two coils of wire, each consisting of several turns of wire wound around opposite sides of the ring. One winding was connected to a galvanometer in order to make apparent any electrical occurrence in the winding. When an electric cell was connected to the second winding, the galvanometer registered a deflection, indicating that a current had flowed in the winding to which it was attached. This current however lasted only as long as contact was being established between the other winding and the cell, and vanished thereafter, even though the battery was sending a steady current through its coil. A momentary deflection in the opposite direction was observed when the battery circuit was broken. Faraday had discovered what is now called mutual

induction, the principle of transformer action; later experiments were to prove that electric currents are induced to flow through a wire whenever the wire is situated in a magnetic field whose strength is changing with time.

Joseph Henry, at the time in Albany but later connected with Princeton University, was simultaneously performing similar experiments. After Sturgeon had constructed the first electromagnet in 1825, Henry made experiments in the new field and in 1829 constructed the most powerful electromagnet that had as yet been made. A year later, surprised by the shock and the spark produced when his battery was disconnected from the winding of his electromagnet, he discovered the phenomenon of electromagnetic induction, self induction in his case, since his magnet had only a single coil. Thinking himself alone in the field, he hesitated to publish his result before obtaining more information. When surprised by the publication of Faraday's discovery, he hastened to publish the results of his work in 1832. He thus lost priority for a discovery in which he was undoubtedly the pioneer. The discoveries of Faraday and Henry, different though they happened to be, were both evidence (unclarified at first) of the production of electric currents by changing magnetic fields.

Faraday proceeded with his experiments. There were too many unknowns in his first experiment. The effect might be caused by the action of the coils on each other, or perhaps the magnetized core might have affected the galvanometer. The obvious procedure was to separate the various possible causes and effects. The same result was observed when the core was magnetized by another magnet instead of current from the cell. The next step clinched the argument: a permanent magnet thrust through the core produced a current in the coil, which flowed as long as the magnet was in motion in the coil's vicinity. The current flowed one way when the north pole of the magnet approached the coil, and the other way when the

north pole was withdrawn. Opposite effects were observed with the south pole.

Thus was discovered the fundamental principle of the dynamo, which converts mechanical energy into electrical energy by causing conductors to move through a magnetic field. But no steady currents had been produced, only intermittent currents. If a conductor could be made to move continuously through a magnetic field, steady currents should result. Accordingly Faraday arranged a copper disc, which could be turned by a crank, in such a way that part of the disc was always between the poles of a permanent magnet. Connections were made to the center of the disc and to its circumference, at a point between the magnet poles and thus in the magnetic field. Current flowed through a galvanometer which was connected to the disc, continuing as long as the disc continued in rotation, and reversing when the direction of rotation of the disc was reversed. Modern dynamos differ from this disc dynamo in many details, but the electrical principle is the same: when a conductor moves across a magnetic field, an electromotive force is generated, and a current will flow if a closed circuit is available.

Oersted and Ampère had proved that a current is surrounded by a magnetic field, and that a magnet in this field will experience a mechanical force, but so far continuous motion had not been produced. In 1821 Faraday observed such continuous motion. Two years later Barlow, using many of Faraday's ideas, modified the disc dynamo and produced a little electric motor. Current from a battery flowed through the disc and the disc rotated, driven by the force between the current and the field of the surrounding magnet. The device is called Barlow's wheel.

Faraday continued his experiments on induction. His own discovery of self induction, evidenced by the spark which passed when current which had been flowing through a coil around an iron core was interrupted, was made in 1834, two years after the similar discovery of Henry, and was published

the next year. Since Henry was more ambitious in the construction of electromagnets and probably built larger ones, it is reasonable to suppose that the effect appeared more definitely in his case.

Faraday's publication of his discovery of electromagnetic induction, as observed by the use of two coils having an iron core, had been the first public evidence of the close relation between electricity and magnetism. He proceeded to study the effect in all its implications, and after a number of disappointments was able to show that when coils consisting of a multitude of turns were used, mutual induction could be observed between coils in the total absence of iron. The induced currents were stronger if an iron core were present, or if a magnet were used. But they were present in any case: A changing current in one coil, because of its changing magnetic field, caused a current to be induced in a second coil adjacent to the first. Or if a coil carrying a steady current from a battery were moved around in the vicinity of a coil connected to a galvanometer, currents were observed just as if a permanent magnet had been moved around. To complete the story Faraday ascertained that his induced currents were the same as battery currents and that the electricity flowing was of the same sort as static electricity. He magnetized needles by passing electricity from statically charged bodies through coils of wire, and decomposed liquids by means of currents from his various sources; in each case the result was the same, no matter how the current had been produced. A multitude of experiments had been necessary to give the clear and simple solution to the problem.

Faraday's studies of electromagnetism, and his abhorrence of action at a distance, without connection, led him to the concept of lines of magnetic and electric force. Although today the reality of these lines in the sense demanded by Faraday is not accepted, the idea has been a useful one; more will be said about this concept in the next chapter.

In 1833 the principle of the conservation of energy was ap-

plied to the new discoveries in electromagnetism. As stated by Lenz, who summarized the results of numerous experiments, the principle demands that whenever a current is induced because of relative motion between a conductor and a magnetic field, the induced current will produce a magnetic field of its own which will be in a direction to oppose further motion of the conductor relative to the original field. This law amounts to one more statement that perpetual motion is impossible; for if the field of the induced current were in a direction to aid the motion, then the increased motion would produce additional current and field, and soon the machine would be turning out prodigious amounts of energy. Thus it is more difficult to drive a dynamo when its terminals are short circuited; when electrical energy is being delivered, more mechanical energy must be available to drive the dynamo in accord with the general principle of the conservation of energy.

The fundamental aspects of electromagnetism had been pretty well explored and Faraday turned to a new subject. Davy and others had known of the decomposition of water and certain salts by the passage of electric current through a solution, but they had not pursued the matter. Faraday's restless demand for knowledge prompted him to look for an explanation of these observations, an experimental explanation which meant more to him than anyone's opinion. He turned to an intensive study of the decomposition of substances by electric currents, a process he was to call electrolysis.

No scientists had surpassed Faraday in his demand for more experimental facts, his unwillingness to believe anything not supported by the results of carefully performed experiments. His work was characterized by a remarkable intuition as to which experiments might be fruitful, as well as a desire to examine every question in every possible experimental manner. He was not content to allow any theory to go untested when a test might be possible. As a result, the theoretical implications of a number of his experimental facts have been considerable, though several of these implications did

not become apparent until after his time; he probably was unaware that his laws of electrolysis clearly indicated the existence of a fundamental unit of electricity, the electron; nor did he know that inherent in his law of electromagnetic induction was evidence regarding the true nature of light waves.

A number of trials soon showed Faraday that the decomposition of substances by passage of electric currents proceeded more rapidly and completely if the substance in question were in a dilute water solution. This fact suggested to him that something was concerned in the process which moved around, since motion from place to place is easier in a liquid than in a solid. The question then arose as to how the elements obtained in the decomposition ever became separated from the original compound. How, in other words, are hydrogen and oxygen separated from water, and how is copper separated from a copper salt dissolved in water? The best views of the time attributed the separation to a direct action of the electric field applied to the plates which were immersed in the solution in order to allow a current to flow. Faraday made quantitative measurements of the mass of metal depositing on plates, or the mass of gas liberated, the quantity of electricity used, the shape and spacing of the plates, and the magnitude of the current employed. He found that the mass of material deposited or liberated in electrolysis depended, not on the strength of the electric field present, but solely on the kind of material liberated and the quantity of electric charge which had passed through the solution. Separation could therefore not have been produced by the field; it must have occurred in the solution. The electric field was responsible for the motion of particles of the substance through the liquid toward one of the plates. The particles responsible for transfer were named by him "ions" * since they travelled through the solution. Each ion was regarded as having a

* From the present participle
are thus travellers or "goers."

definite electrical charge, which it gave up on arriving at the plate where it was deposited or liberated.

These experiments resulted in the establishment of Faraday's two laws of electrolysis: The amount of matter liberated from a solution by the passage of electricity depends only on the relative atomic mass of the substance liberated and the quantity of electricity which has passed; the relative amounts of two substances which are liberated by the same quantity of electricity (the same current flowing for the same time) bear the same relation as do the "chemical combining equivalents" of the two substances. The chemical equivalents of two substances are the relative amounts of each substance which will combine chemically with the other without leaving any portion of either uncombined; if the substances do not combine, then the chemical equivalents are the relative amounts which will displace the same amount of hydrogen from a compound.

Ions are charged atoms or groups of atoms. The concept of ions has more recently been applied to the conduction of electricity through gases. It is now known that, whether the ion exists in a liquid or a gas, the charge on each ion must be a small whole number of elementary (electronic) charges. In electrolysis, the number of unit charges on each ion is determined by the chemical combining properties of the substance in question, principally the chemical property that is called valence.

Besides the fundamental significance of the information obtained, these researches led to two further results: In the first place they made available the first accurate means for measuring the strength of an electric current by weighing the silver or other substance deposited by the current in a given time. In the second they led Faraday to an explanation of the action of the voltaic cell, which was found to be the opposite of the action in his decomposition cells (called voltammeters). In the cell chemical energy causes the ions to move and give up their charges to one of the plates, which charge then is available for sending a current through an external circuit; in the voltam-

meter electrical energy drives the ions through the solution.

Even now the work of Faraday was not complete. He was still thinking over his experiments on induction, still trying to conquer the notion of action at a distance. How could a magnet in one place produce a current in a wire at a different place? His attempts to solve this problem led him to the invention of lines of force, a concept he may have had for some time without wishing to publish it until experimental verification was obtained. He knew that magnetic force was not always directed in the straight line between the magnet and the point where the force was measured. He now found the same thing to be true of electric force; the attraction between two charged bodies did not disappear when a conducting screen was placed between the two bodies without however completely enclosing either. In his mind these facts ruled out action at a distance. One might think that when postulating action at a distance, almost any sort of action might be assumed with equal reason, even action that follows curved lines. But Faraday could not accept the idea and postulated instead lines of magnetic or electric force which he imagined as physical realities. He gave these lines physical properties; they were supposed to be under tension, so that they would contract along their length and expand sideways. His belief was strengthened by his studies of electromagnetic induction, where the electromotive force depends, not on the strength of the field but on the actual number of lines cut by the moving conductor. In the case of self induction, lines of force around a coil in which a current is flowing collapse across the coil when the current is interrupted, thus inducing an electromotive force which results in a spark or a shock.

One would think that even this genius would have burned itself out at last; but instead, Faraday turned to the study of still another field, that of light.

Feeling that the essential simplicity of nature demanded that light should not be essentially different from electricity or magnetism, he set about trying to show the expected re-

lation. Here most of his experiments failed because of his lack of sufficiently delicate and powerful apparatus. He did however succeed in proving that a ray of polarized light passed through a dielectric, such as a transparent insulating substance or certain liquids between the poles of a powerful magnet, was affected by the magnetic field. The plane of polarization of the light was rotated. Other experiments in this branch of physics were brought to success later by Kerr, who obtained a similar effect by passing polarized light through substances in powerful electric fields. The later discoveries of Zeeman, relating to other effects of magnetic fields on light, could not be found by Faraday, since the necessary apparatus had not as yet been developed. Nor did Faraday suspect the later inclusion of his discoveries in the electromagnetic theory of light.

In further experiments, Faraday showed that not only iron and steel, but in fact many other substances showed certain magnetic properties. Some (paramagnetic) would behave in the same way as iron and steel, but not so strongly; a rod of the substance in a magnetic field would turn into a position parallel to the field. Others (diamagnetic) would orient themselves at right angles to the field. Of course the ferromagnetic substances are the only ones that can be strongly magnetized.

The next chapter will relate how Maxwell brought the ideas of Faraday and his contemporaries to glorious achievement in his mathematical theory of electromagnetism, as well as the electromagnetic theory of light. Science has paid tribute to Faraday by naming two physical units after him. The farad is the unit of electrical capacity, related to the ability of a body or condenser to store electricity; the faraday is a unit occurring in electrolysis.

Now at last the great man was forced to rest, after a lifetime of achievement. When Faraday died in 1867 the world lost one of its great scientists and philosophers, and science lost one of her most revered diciples.

Chapter 7

FROM MAXWELL TO RADAR

AT ABOUT the middle of the last century the development of physics from its early beginnings, as traced in previous chapters, had led to a high degree of achievement and had presented complete justification for the experimental method. The wave theory of light had been established and the kinetic theory of gases rested at last on a firm foundation. The laws of electricity and magnetism, as well as those of electromagnetic induction in which electricity and magnetism meet, had been discovered and put to use. Foundations for the modern electrical industry had been laid and the principles underlying the telephone, telegraph, motors and generators had been established. Theoretical studies in the subject of dynamics had produced accurate descriptions of the observed motions of the heavenly bodies.

The culmination of the classical period of physics was at hand. When at last Maxwell had shown in his beautiful theory, based on the work of Faraday and his contemporaries and supported by experiments of Hertz, that waves of light are really electromagnetic waves and that electricity, magnetism and light are closely related, it is no wonder that scientists were convinced of the completion of the quest for truth. All physical knowledge appeared to have been discovered and combined in a consistent whole.

James Clerk Maxwell lived from 1831 to 1879. He was born in Edinburgh, where his early life was spent and where he

received his education, attending the university and visiting meetings of the Royal Society of Edinburgh. He later spent some time at Cambridge University, working in the field of mathematics and the physical sciences. As his mathematical ability and knowledge of physical discoveries increased he recognized the fundamental importance of Faraday's experiments and resolved to put his results in mathematical form, a thing which Faraday had been unable to do.

It will be recalled that in order to explain induction, as well as electric and magnetic attraction, and at the same time to dispense with the untenable concept of action at a distance, Faraday had invented lines of force which he regarded as having physical reality. Faraday believed that these lines were in some fashion related to the space in which they were supposed to exist, though experiment had told him little about what the relation might be. He only knew that attraction could be observed and induction produced around the edges of a shield, so that the lines might be curved and turn corners. But did these effects depend in any way on the nature of the space in which lines of force exist? The wave theory of light had demanded the invention of a material medium, called the ether, which was supposed to fill all space and in which light waves were supposed to travel. Why not assume a medium to support lines of force?

Faraday proceeded to investigate as far as possible the effect of the medium between two bodies subject to electric forces. This he did by placing different substances between the bodies and looking for any new effects which might result. His arrangement was similar to that previously described, in which an electric charge is given to a body, not by touching it to another charged body but by induction. He constructed two identical parallel-plate condensers, each consisting of a pair of conducting plates between which sheets of glass, rubber, or other substance might be placed; or the space between the plates might simply contain air. The two plates of each condenser are the two conducting bodies in the induc-

tion experiment: if a charge is placed on one of them, then a charge will be induced on the other.

In the experiment, one plate from each condenser was connected to a common wire, the other plates being free. An electric charge was placed upon the connected plates, and Faraday looked to see how much charge had been induced on the free plates. When air was the medium in both condensers, both free plates showed the same amount of induced charge, but when one condenser contained air and the other a slab of sulphur the free plate beyond the sulphur showed a greater induced charge than did the one in which air was the medium.

Here was clear evidence that the medium between conductors plays a most important part in electrostatic induction. The property of the medium which determines the relative ease with which induction can occur, Faraday named "specific inductive capacity." Since an insulating medium is called a dielectric, another name for the property is "dielectric constant." Not only is electrostatic induction affected by the medium, but also electrostatic forces; the force between two charged bodies is less when they are separated by sulphur than when air is the only medium between them.

Having proved that the facts of electrostatic induction depend on the medium, there was nothing else to do but assume that the lines of force held responsible for the induction were intimately connected with the medium in which they exist. Faraday regarded the medium as polarized; he imagined that the medium was filled with small electric charges which under the action of electric forces were displaced from positions of equilibrium. Lines of force in the medium then became lines along which polarization had been produced, or lines along which charges had been slightly displaced.

It must be noted that since induction can be produced in a vacuum, the assumption of an ether or something similar appears to be necessary. What then about the little charges? This difficulty was avoided, as in fact were most difficulties with the hypothetical ether, by a change in emphasis. Lines

of force were supposed to end on induced charges. By concentrating on the induced charges themselves, and by speaking of "tubes of induction," attention was directed away from the complex mechanism inherent in the assumption of the ether. Much has been gained from the emphasis of present-day science on quantities subject to direct observation, and Einstein among others has shown the advantage of sweeping away outmoded concepts, of which the impossible ether is one. It is a mystery how anything with so many inherent inconsistencies could have lasted so long.

However, at the time when Maxwell was ready to make contributions to physical science, the medium had attained an exalted position. Light was supposed to travel in it, an elastic solid which offered no resistance to the motion of the planets; electric and magnetic forces also were supposed to depend on the medium. It was natural that this medium was to become the basis of Maxwell's theory, which was first announced in 1864.

Maxwell expressed the experimental discoveries of Faraday and Ampère in mathematical language and worked out logical implications. The seat of electric and magnetic forces was supposed to be the medium, whether the all-pervading ether or some material substance such as glass or mica. This theory produced a system of equations which gave the correct relation between electric and magnetic forces and correctly explained the facts of electromagnetic induction, which was to be expected, since corresponding experimental facts had furnished the starting point. Elastic strains in the ether associated with electric forces, as well as the displacement currents of Faraday, played an important role. In fact, the presence of displaceable charges subject to elastic forces in the medium seemed to be required if the medium were to be able to propagate wave motion.

The theory of Maxwell not only explained all previous observations but indicated the existence of new effects as yet unobserved, principally the existence of a new kind of wave

motion. Transverse waves were predicted, involving periodic displacements of the charges supposed to exist in the medium; these displacements caused both periodic electric and magnetic forces and resulted from them. It was predicted that the velocity of the waves in empty space should be the same as the velocity of light.

The question of the velocity of electromagnetic waves raises an interesting point. Two systems of electrical units have been used, both fundamental and absolute: The electrostatic system is defined on the basis of the electric force between charged bodies, while the electromagnetic system depends on the magnetic effect of a current of electricity. Units exist in either system for all electrical quantities. Maxwell actually predicted that the velocity of his waves in empty space should be the same as the ratio between units in the two systems. However, experimental measurement of this ratio had shown its equality to the velocity of light as measured in centimeters per second. As experimental accuracy has increased it has become increasingly evident that an actual equality exists. This very fact might indicate that light waves are electromagnetic in nature.

Here indeed was justification for Faraday's views on the inherent unity of nature, and the relation between electricity, magnetism and light.

Experimental justification of the new theory was not long in appearing. In experiments performed in Berlin in 1876, the American physicist Rowland showed that the magnetic effects of a charged body in motion were similar to the magnetic effects of a current flowing through a wire. He gilded the circumference of an ebonite disc, which was rotated rapidly after the conducting portion had been given a charge. The amount of charge was known, also the speed of rotation of the disc. When the magnetic effect was observed, it was found that there was no difference between the magnetic field produced by the moving charge and that produced when the same amount of charge per unit time moves along a wire carrying

a current. The magnetic fields were identical, both in strength and in direction.

Although Rowland actually compared conduction currents to convection currents, his experiment made more reasonable the assumption of displacement currents in the medium. But the most complete justification of the theory of Maxwell came ten years later in the experiments of Hertz, performed at the instigation of Helmholtz.

The apparatus of Hertz was actually the first wireless or radio apparatus, although he did not use it for the transmission of messages. Joseph Henry had used a similar apparatus in 1845 and had transmitted electromagnetic energy through space over short distances, though his experiment came before Maxwell's theory and he probably did not realize he was working with electromagnetic waves. Hertz produced and measured the waves predicted by Maxwell; his source was an induction coil, well known development of the pioneer work of Faraday. The terminals of the secondary or high-voltage winding, between which a spark passes when a battery is connected to the primary, were connected to metal plates and a spark gap consisting of small metal spheres. The receiver or detector of the waves was a metal ring, broken at one point to form a small gap. Waves of electromagnetic energy were produced by the transmitter and oscillating currents were produced in the ring of the receiver, becoming evident by the spark produced in the gap of the receiving ring. Early wireless outfits were similar to the apparatus used by Hertz, though greater receiver sensitivity increased the distance over which messages could be sent.

Hertz went farther than merely producing the waves. He caused them to be reflected from a metal sheet and found that they were reflected in the same way as light waves. He also produced interference between the direct and the reflected wave, as is the case with light waves in the production of Newton's rings. By moving his receiver back and forth, toward the reflector and then away from it, he observed the standing

waves which were produced, and noticed that sparks occurred in his receiver only at distances from the reflector corresponding to maximum vibration in the standing wave, where the electric forces in the wave were greatest.

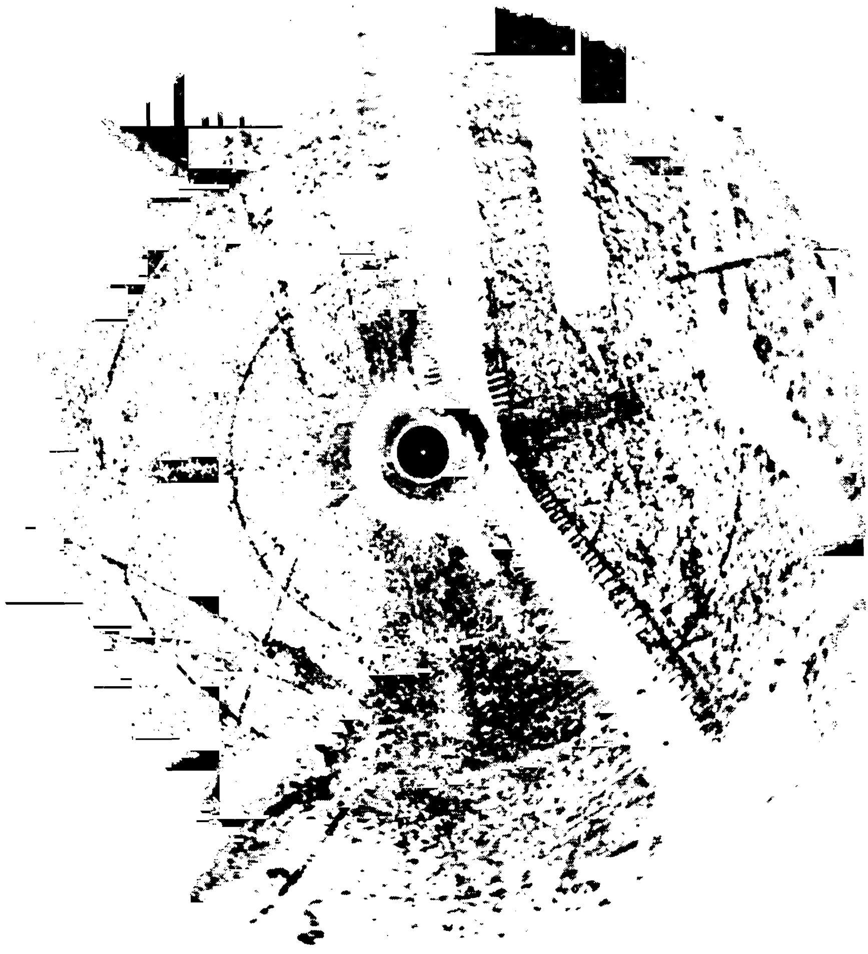
Recent measurements show that the velocity of radio waves is exactly the same as the velocity of light in empty space. The complete acceptance of the fact that light consists of electromagnetic waves followed as a matter of course and Maxwell's theory is often called the electromagnetic theory of light. The spectrum of electromagnetic waves has been extended, until now it includes the short gamma and x-rays; ultraviolet, visible and the longer infra-red and heat waves; and finally all radio waves from the shortest to the longest.

The fact that radio waves travel with definite and measurable velocity has made possible one of the most striking of modern developments, that of measuring the distance to an object by measuring the time it takes for a radio signal to travel to the object and be reflected back. The first successful observation of this sort was made in America by Breit and Tuve, who in 1926 observed the reflection of signals from the ionosphere, the ionized layer of the upper atmosphere which had been known to reflect short radio waves back to the earth. Electromagnetic energy was transmitted in short powerful pulses; when the time required for each pulse to complete a round trip was observed, knowledge of the velocity made it a simple matter to compute the distance traversed.

The radio locator, or radar (radio direction and ranging) system, utilizes the same essential technique. Concentration of the beam by means of parabolic reflectors or other means also makes possible determination of the direction of the object from which the energy is reflected. Development of electronic devices for measuring time intervals less than a millionth of a second has made radar ranging an accurate science, and distances observed by radar are often more accurate than those determined by optical range finders. Although Maxwell would probably be dazed by the complexity

of detail in a radar system, he would easily understand the principles underlying its operation.

Maxwell's theoretical contribution was the culmination of the classical period of physics. Near the end of the last century it was believed that at least in the field of physics all things were known and all important natural laws discovered. A beautiful and logical science had been constructed and it was inconceivable that a structure of such perfection should not be the all-inclusive end which had been sought. Physicists congratulated themselves and settled down to routine measurements involving one further place of decimals, the only work they believed still left for them. Little did they dream of the loaded bombshells of the electron theory, relativity, and the quantum theory which were soon to explode in their midst.



Courtesy M.I.T. Radiation Laboratory

Radar scope picture of New York city and vicinity.

Chapter 8

CATHODE RAYS AND X-RAYS

THE SPURT of scientific activity noted in preceding chapters had brought physics to a high degree of development, which was believed to give a true and final picture of the structure and operation of the physical universe. Somewhat arbitrarily, physics has been divided into two categories, classical and modern. The unifying theory of Maxwell, with its experimental verifications, brought the classical period to a conclusion. Modern physics, starting with the study of electrical discharges in vacuum tubes and accelerated by the discovery of x-rays and radioactivity, is concerned principally with the atom and its components. For a number of years interest centered on the electron, and electron physics was an active field. More recently physicists have been exploring the atomic nucleus, tiny inner core of the atom.

Modern physics started out with a few experimental discoveries which were utterly incomprehensible in terms of the established laws and beliefs of physical science. The discovery of the electron was the gateway into the new field of atomic physics; for years the electron played a major role in scientific development and now forms the basis of the science and art of electronics.

The history of the electron really starts with Faraday's discovery of the laws of electrolysis. Faraday had shown that the mass of any particular metal deposited from an electrolyte depends solely on the quantity of the electric charge which

passes through the solution, and not on the strength of the current used. If the current is stronger, then the material will be deposited more rapidly. Also proved was the fact that the same current flowing for the same time will deposit from their respective solutions amounts of different substances which are proportional to their chemical combining equivalents. If silver and hydrogen are the substances being deposited and liberated, then, since these elements are univalent, the masses obtained in electrolysis by the passage of a given current for a specified time will be proportional to the respective atomic weights.

The implication is clear, that the same number of atoms of each substance have been freed from the solution.

Avogadro had shown that equal volumes of different gases, under standard conditions, contain the same number of molecules. It is generally known that a mole * of any gas, at standard temperature and pressure, occupies the same volume, 22.4 liters, and thus according to Avogadro's law contains the same number of molecules. Apparently a gram-atomic-weight of any substance, whether solid, liquid or gas, contains the same number of atoms. The ratio of the atomic weights is the ratio of the weights of single atoms; or the ratio of the weights of equal numbers of atoms, especially that number present in a sample whose mass in grams is equal to the atomic weight.

The fact that in electrolysis the same number of atoms of different univalent substances are liberated by the passage of a given quantity of electricity implies that associated with each univalent ion there is a definite amount of electric charge; and, further, that this electric charge appears, at least in electrolysis, in the form of discrete units, atoms of electricity. It also appears that the charge on each univalent ion must be the same, no matter what the substance. If the valence is two, then half as many atoms will be liberated, and each ion apparently carries a double charge.

* A mole of gas is the quantity whose mass in grams is equal to the molecular weight of the gas; a gram-molecular weight.

Although Faraday must have recognized the need for an assumption of this atomicity, he said little about it. Maxwell felt that Faraday's researches in electrolysis seemed to demand acceptance of the idea that elecricity exists in the form of molecules or other discrete units. He adds however that a complete knowledge of the phenomena would probably clear up the difficulty and eliminate the necessity for such an assumption. Emphasis had been placed on a continuous medium, supporting electric and magnetic forces and the propagation of light waves; doubtless electricity was regarded as so intangible that talk about atoms of electricity was deemed senseless.

But it became progressively difficult to explain Faraday's laws in any other way. Helmholtz spoke of the atomic nature of electricity as a tenable assumption, and Stoney in 1874 went so far as to name the assumed electrical unit; he called it the electron.

By dividing the amount of charge needed to deposit a gram-atom of silver by the number of atoms in a gram-atomic-weight it was possible to estimate the amount of charge associated with the hypothetical unit. Stoney made the calculation, although the number of atoms in a gram-atom was not known with accuracy.

The conception of the atomic nature of electricity had thus been introduced as a possible explanation of experimental observations in electrolysis. It was to lie dormant for years, accepted by few, until forced upon the attention of the scientific world by studies of the discharge of electricity in gases.

It had been known for some time that a spark will pass more easily through a partially-evacuated tube than through air at atmospheric pressure. The indefatigable Faraday had worked with such discharge tubes and had observed how the discharge changed as air was pumped out. He would have made more discoveries if his pump had been more powerful.

Imagine a long glass tube, connected through a side tube to a vacuum pump. Metal electrodes sealed into each end of

the tube are connected to the secondary terminals of an induction coil in order to obtain high voltage for the gaseous discharge; the distance between electrodes is too great for a spark to pass between them unless air is pumped from the tube.

When the induction coil is set in operation and the pump started, at first nothing is seen. Then as the air pressure in the tube decreases, long thin streamers of light stretch along the length of the tube between electrodes, fairly straight but weaving in and out among each other. As the pressure becomes less the streamers are less sharply defined and more diffuse, spreading out to fill the tube as in luminious-tube electric signs. At one end of the tube the discharge soon moves away from the electrode, leaving a space called the Faraday dark space. As the pressure continues to decrease the column of luminosity breaks up into striations, portions alternately light and dark. The Faraday dark space grows in size and soon near the electrode at that end of the tube the cathode glow appears. The cathode is the electrode which is connected to the negative terminal of the induction coil. Finally the cathode glow moves away from the electrode, leaving the Crookes dark space. Meanwhile the striations in the positive column of the discharge have moved farther apart and soon the entire discharge weakens and fades out altogether; the tube now contains a fairly good vacuum.

Although the discharge has disappeared there is still something else to see, for the walls of the tube begin to fluoresce with a flickering pale greenish light, especially prominent in parts of the tube opposite the cathode.

The study of gaseous discharge tubes provides a classic reply to those who ask what is the use of research in pure science, who are not satisfied unless the results are to have some utilitarian and economic importance. At this stage such a person would have said there could be no use for the pretty streamers and glows. Why do scientists study the constitution of stars which for practical purposes are hopelessly

beyond our reach? Knowledge must be increased and the unknown explored. Every scientific advance is bound to benefit mankind in one way or another. The glows and discharges of the impractical scientists have led to knowledge of x-rays useful in the diagnosing and curing of human ills; to the vacuum tubes of modern radio and electronics, basis of a multimillion dollar industry which has furnished pleasure, safety, and a new technology. If our questioner was unable to see the future developments of these researches, neither could the scientists themselves; but the scientists were too busy finding out about nature to care very much. In spite of the premium placed today on scientific ability by the entrance of industry on a large scale into scientific research, many still tread in the footsteps of Faraday, following their trained imagination into the unknown, eager to see where they will be led. It is true that the lag between fundamental discovery and practical application is much less than ever before, and the immense achievement of the past indicates more strongly than ever that pure science is the inevitable and essential predecessor of practical application.

Hittorf had noticed in 1869 that the green fluorescence on the walls of discharge tubes occurred only on those parts of the glass that could be seen by the cathode. The anode or positive terminal cast a shadow in which no fluorescence appeared. Artificial objects placed in the tube also cast shadows. Whatever was responsible for the greenish glow must have come from the cathode, and apparently travelled in straight lines, since the edges of the shadow were sharply defined. Crookes, as well as Plücker, constructed many of these tubes, of different kinds. It became increasingly evident that some sort of radiation was emitted from the cathode.

The true nature of cathode rays was widely discussed, with much disagreement. Could they be composed of streams of particles, or were they simply a new form of electromagnetic radiation? Crookes spoke of the possibility of radiant matter, as he called it; he was convinced that this radiation could

not be of the usual sort, for he had discovered that the rays could be deflected by means of a magnet. He noted that the deflection occurred in such a direction as to show the existence on the assumed particles of a negative charge. Perrin (active in the kinetic theory of gases) confirmed the observation in 1895 when he so deflected the cathode-ray beam that it fell upon a metal plate connected to an electrometer.

Clarity increased as experimental evidence grew, Lenard succeeded in constructing a tube with a thin window, permitting cathode rays to leave the tube and excite luminescence in the air outside. Schuster in 1890 caused the rays to be deflected in a magnetic field and, on the assumption that charged material particles were involved, measured the ratio of their charge to their mass. A relation exists between such quantities as the charge on each particle, the mass, the velocity of the particles in the tube, which depends on the applied voltage, the strength of the magnetic field, and the resulting deflection. All these quantities can be measured directly, except the ratio of charge to mass, which is the desired result and can be computed from the measurements. Charge or mass alone is not given by this sort of experiment.

Schuster found that the ratio of charge to mass was much greater than was the case for hydrogen ions in electrolysis. He assumed that the mass of a particle in the cathode-ray beam was the same as that of an atom, with the result that the charge as computed from the ratio came out very much larger than the charge on a hydrogen ion. He would have been nearer the truth had he assumed the charges were the same and the mass very much smaller. The choice was determined by the general belief that streams of charged atoms were involved, and the conviction that the atom was the ultimate particle.

Ideas of the time relating to the conduction of electricity in gases were extremely vague. It was known that gases conduct electricity to a certain extent, especially when the gas is rarified, and it was believed that gaseous conduction might be related in some manner to electrolytic conduction. Knowing

little about the intrinsic nature of molecules, to say nothing of atoms, physicists of the day could not understand how ions could be formed in air; the same ideas were brought forward as had plagued Faraday at an earlier date: molecules must be rent asunder by the applied electric field.

In 1895 occurred a discovery, made more or less by chance, that was to have great importance in the development of physics. While working with cathode-ray tubes, Röntgen noticed that a screen of fluorescent material glowed when in the vicinity of the tube, not necessarily within it. He noticed that the fluorescence was still present when thin opaque objects were placed between tube and screen. An easy step was the discovery that photographic plates wrapped in black paper were nevertheless affected by the radiation which apparently came from his experimental tube. Because this radiation seemed so mysterious he named it x-radiation. It has also been called Röntgen radiation.

The new rays appeared to have additional properties. They possessed the power to make air conducting to electricity. A charged electroscope which under ordinary conditions would hold its charge for hours would lose the charge in a few seconds if exposed to x-rays. With eagerness, physicists began to study these rays in attempts to find out more about them.

The true nature of x-rays did not appear at once. They were able to pass through opaque objects impenetrable to visible light. They were not deviated by glass prisms. Their nature became apparent in 1903 when Barkla established the fact that they were really transverse waves, probably electromagnetic waves differing from light and from Hertzian waves only in their very short wave length. Barkla allowed the rays to be scattered or diffusely reflected by matter in such a way that the scattered beam proceeded in a direction at right angles to the original beam from the tube. The scattered beam was again scattered at right angles from another object. An examination of intensities in the second scattered beam

showed that this beam was polarized, in fact the experiment is similar to an optical experiment in which light is polarized by reflection. Such polarization is possible in a beam of transverse waves, not in a beam of longitudinal waves; reflection at right angles eliminates certain vibrations from an incident transverse wave, allowing only those vibrations perpendicular to both incident and scattered rays to get through.

It has been noted that x-rays increase the conductivity of air. Thomson and Rutherford were able to show experimentally that conduction of electricity in gases depended on the formation of gaseous ions, for the increased conductivity of air which had been exposed to x-rays vanished when the air was sucked through a liquid, or closely packed cotton, which aided the recombination of positive and negative ions into neutral molecules as well as absorbing some of the ions. The nature of gaseous ions was still unknown, since very little was yet known concerning the true nature of molecules or atoms. This knowledge arrived later when Rutherford produced his model of the nuclear atom.

Experiments continued on the ratio of charge to mass of particles in a cathode-ray beam. Experiments performed by J. J. Thomson, commencing in 1895, were a refinement of the earlier ones of Schuster. With magnetic deflection of the particles he combined a perpendicular deflection produced by electrically charged plates, for greater accuracy and ease of measurement. He also found the ratio larger than was true for the hydrogen ion in electrolysis, but correctly ascribed this result to the smaller mass of the particle, very much smaller than that of the hydrogen atom. Electrons in the cathode-ray beam have the same charge as the hydrogen ion, but the electron is very much lighter. It was significant that at about this time it was found that particles ejected from metals under the action of light in the photoelectric effect also showed a negative charge, and the same ratio of charge to mass.

Thomson assumed that an atom consists of small negative

Courtesy M.I.T. News Service

Preparing to adjust the M.I.T. two million volt generator.

charges embedded in a larger sphere of positive charge. X-rays or ultraviolet light incident upon the atoms in a piece of matter then were able to force negative charges out of the atom, in a manner which was still mysterious but might depend on electric forces present in electromagnetic radiation. Cathode rays were supposed to be streams of electrons which had been knocked out of atoms in the cathode by the intense electric forces applied. X-rays were produced by the impact of cathode rays on glass or metal.

The seeds of modern physics had been sown and the harvest was beginning to show itself above the ground. It was to grow by leaps and bounds, no sooner appearing ripe for harvesting than new spurts would send physicists hastily into the fields, eagerly watching their crops and wondering what the next development might turn out to be.

Chapter 9

RADIOACTIVITY

Scientific discoveries have occasionally been anticipated by many centuries. Although divine revelation and philosophical cogitation are not generally regarded as sources of scientific truth, it sometimes happens that a hunch is eventually found to have been a pretty good guess. The atomistic theories of the early Greeks have been verified to a degree by Dalton and his contemporaries. The Copernican idea of the solar system was advanced long before the central and dominating position of the sun could be proved with any semblance of scientific exactness. If it is true that early glimpses into the realities of nature are occasionally awarded to men of superior insight, then pioneers among the alchemists should join the list of those endowed with scientific clairvoyance.

The alchemists believed that if the proper secret could be found, one chemical element could be changed at will into another. They were especially interested in the possibility of changing lead and other base metals into gold. It would be interesting to know who first suggested the possibility of such a change; no credit for originality of thought can be allowed his followers, who slavishly continued his search for a number of centuries. But the pioneer, if his identity were known, would rank with Democritus, for during the present century the secret has been found, the philosopher's stone discovered. Heralded by the appearance of radioactivity, achievements in

the realm of nuclear physics have surpassed the wildest dreams of the alchemists.

The discovery of radioactivity followed shortly after Röntgen's first detection of x-rays, and in a sense there was a causal relation between the two.

X-rays appeared to be derived from portions of a cathode-ray tube exhibiting fluorescence; thence moving outward, they were able to penetrate opaque objects and cause external bodies to fluoresce. Were the rays produced by the fluorescence of the tube or did they cause it? Could it be true that substances such as calcium or uranium compounds which showed fluorescent effects after exposure to sunlight, might be natural sources of x-radiation?

The question was investigated by Henri Becquerel in France. He exposed various substances to sunlight, then placed them near photographic plates which had been wrapped in black paper. If x-rays were present they would pass through the opaque wrapping and register an effect upon the sensitive plate. He was naturally gratified to find that uranium compounds did in fact show evidence of the production of penetrating radiation. It is well that his experiments did not cease at this point, for he would have missed a great discovery. He looked for any possible action of uranium compounds which had not recently been exposed to sunlight in order to produce fluorescence, and to his great surprise still found the characteristic blackening of the plates. The discovery was made in 1896; the property of substances to emit penetrating radiation without external assistance was called radioactivity.

The radiations from uranium were at first compared to x-rays, although they were found to be more penetrating. It appeared later that they were also more complex.

It was natural to inquire at this point whether other substances, perhaps to a certain extent all substances, might be radioactive. This question immediately became the subject for investigation by Pierre and Marie Curie. Pierre Curie

was already noted for his researches in magnetism and piezoelectricity, and Marie Curie was a scientist in her own right; with Schmidt she had ascertained that thorium as well as uranium possessed radioactive properties. After Pierre's accidental death, his wife carried on the work.

Madame Curie soon discovered that certain uranium ores were more strongly radioactive than the element uranium itself. This fact might indicate that the activity of uranium depends in some way on its physical or chemical condition, or it might indicate the presence in the uranium ore of some other element, more strongly radioactive than pure uranium. It soon appeared that the activity of uranium did not depend on temperature or on its state of chemical combination. The implication was inescapable that in the uranium ore there was some new and strongly radiating substance as yet unknown.

Photographic plates were first used to detect the radiations. It appeared that a more sensitive method was desirable, both to detect weaker radiations and to compare with greater accuracy radiations of different strength. The method adopted, and since used almost universally in similar investigations, depends on the ability of the radiation to ionize air or other gases. At first a simple electroscope was used; a long narrow strip of thin goldleaf is fastened to a metal support, mounted on insulators in a glass-sided box to eliminate disturbance from draughts of air. An electric charge is given to the leaf in any convenient manner, whereupon electric forces cause the leaf to move out at an angle to the support, the amount of the deviation being an indication of the quantity of charge on the leaf. More accurate means for accomplishing the same result were later developed.

When x-rays or rays from radioactive substances pass through an electroscope, the air or other gas is ionized; molecules are torn apart and the gas becomes conducting. Charge is now able to depart from the leaf system and the leaf gradually drops back to its original position at a rate depending on

the amount of ionization present, which in turn is a function of the intensity of incident radiation. By use of the electroscope the presence of minute quantities of radioactive material may be detected in a very short time.

The particular mineral studied by Madame Curie was pitchblende, an ore which contains a large precentage of uranium oxide. A ton of this material, obtained from the Austrian mine at Joachimsthal in Bohemia, was given her by the Austrian government and expenses for her research were met in part by donations from the Rothschilds. In 1898 she set out systematically to separate the pitchblende into its various constituents, testing each portion for possible radioactivity.

The essential constituents of pitchblende are uranium in chemical combination, principally the oxide; bismuth, barium, and lead. When separated out, the uranium showed the expected activity. Bismuth and barium from the ore showed strong activity which was surprising since these elements are not usually radioactive. It was clear that some new element or elements, strongly radioactive, were combined with these samples of bismuth and barium. Madame Curie gave the name polonium, in honor of her native Poland, to the active element associated with the bismuth. To the element occurring with the barium she gave the name radium because of its remarkable activity.

She now proceeded with attempts to separate the new elements. The chemical properties of radium are very similar to those of barium, and these elements appeared together when separated from uranium by chemical means. Their physical properties however are slightly different and their separation by physical methods appeared possible, though difficult. Barium and radium may be separated by the process of fractional crystallization: when a solution is cooled, one will crystallize a little more rapidly than the other. By pouring off the remaining liquid at just the right time, and by repeating the process a large number of times, a substance

was separated which was very much more strongly radioactive than any known element: the radium she was seeking.

The work was carried out in a small temporary building in Paris. Her laboratory resembled in many ways a soap factory, with huge kettles suspended over fires and many smaller vessels here and there in which liquid was allowed to stand and crystallize. The process was extremely laborious; from the ton of pitchblende she was able to obtain about a fifth of a gram of radium salt, which however was over two million times as active weight for weight as pure uranium. Pure metallic radium was obtained a few years later.

In true scientific spirit Madame Curie presented her discovery freely to the world. Lacking royalty payments which would have resulted from a patent, she was unable to purchase radium needed for further experiments; her need was later supplied through the generosity of American women who by popular subscription raised approximately $70,000 to purchase for her a gram of the element she had discovered and isolated. More recently a second gram was presented to her for further scientific work in which her daughter Irene collaborated. Before the Second World War the largest supply of radium under one roof was in the Memorial Hospital in New York City, where eight grams of the precious metal were used in the treatment of cancer.

The world's standard sample of radium was prepared by Madame Curie, and has been preserved in Paris. Twenty-two milligrams of pure radium chloride, carefully prepared and permanently sealed in a container through whose walls radiation can pass, are available for the standardization of radioactive sources.

During the years that radium was being isolated and purified, studies were in progress on the nature of the radiations. As early as 1899 Rutherford had determined that these radiations were probably somewhat different from x-rays. He allowed the rays from uranium to pass through various thickness of metal foil and concluded that at least two kinds of

radiation were present, one kind being able to pass through greater thicknesses of metal than the other. The less penetrating rays he named alpha rays, while those possessing more penetrating power were called beta rays. Later Villard detected a third kind of radiation which was even more penetrating. Following the system initiated by Rutherford, the latter was called gamma radiation.

Elster and Geitel had noticed that the ionizing power of the rays was changed in the presence of a magnetic field, and in 1899 Giesel found that beta rays could be deflected magnetically. Indeed these rays must contain particles similar to those in a beam of cathode rays; they were deflected in the same manner by a magnetic field, and apparently had about the same value of the ratio of charge to mass. X-rays cannot be deflected by a magnetic field.

Madame Curie soon found that alpha rays must also consist of streams of material particles. X-rays passing through metal foils are absorbed in proportion to the foil thickness, but alpha rays were absorbed more rapidly. A stream of rapidly moving particles would be slowed up by the first foils encountered, with the result that absorption by succeeding foils would be all the more probable; x-rays behave quite differently. The material nature of alpha rays was shown in 1903 when Rutherford proved that these rays as well as beta rays could be deflected by a magnet, though the deflection was in the opposite direction. As had been predicted by Strutt in 1901, alpha particles carry positive charges; they are also much heavier than beta particles, or the particles in a beam of cathode rays.

Alpha particles are easy to observe. At first they were counted by the scintillations produced when they strike a screen of zinc sulphide. The charge on a given number of particles can be determined by collecting them on a metal plate connected to an electrometer, and the ratio of charge to mass found by means of deflection experiments. It turned out that each particle carried a positive charge whose magnitude

was just twice that of the charge of a beta particle or cathode-ray particle; the mass was found to be about four times that of the hydrogen atom, nearly equal to that of the atom of helium.

Absorption experiments indicated that gamma radiation was very similar to x-radiation, though perhaps more penetrating. In no experiment could these rays be deflected by a magnetic field. Complete proof of the similarity between gamma and x-rays came a few years later; both are forms of electromagnetic radiation, gamma rays having greater penetrating power and shorter wave lengths, unless extremely high voltages are used in the production of x-rays.

If a speck of radium is placed in a narrow hole in a deep block of lead, radiation emerges in a narrow beam from the opening. When a magnetic field is applied across the face of the block, gamma rays will not be affected, but alpha rays will be bent slightly and beta rays more strongly and in the opposite direction.

Radium produces large quantities of heat, sufficient to raise the temperature of an equal mass of water from freezing to boiling in less than an hour. What new kind of matter was this that could apparenly give off unlimited quantities of radiation, thermal energy, and even matter, and yet remain sensibly unchanged?

Madame Curie had noticed that objects in the vicinity of radioactive material themselves became radioactive. This phenomenon was called induced radioactivity, though there was no obvious explanation as to how radioactiviy might be induced. The explanation was left for Rutherford, who in 1900 had noticed that thorium emits a radioactive gas. The active properties of thorium emanation, or thoron, decrease rapidly, but a thin invisible coating of active material is left on surfaces which have been exposed to the gas. A similar gas, called radium emanation, or radon, is emitted by radium. Rutherford studied the decay of the activity of these gases, as well as the increase in activity of the active deposit and in

1903, with Soddy, announced his famous theory of radioactive disintegration, which has been completely verified in numerous experiments.

The theory of Rutherford and Soddy constituted a revolution in scientific thought. For the first time in history true scientists had announced that one element may change into another, augmenting their announcement with adequate experimental support.

Radioactive elements are unstable. Experiments show what fraction of the atoms present in a sample will disintegrate in a given time, but not which ones. An atom of thorium, when it disintegrates, emits a particle and becomes an atom of thoron gas, a new element. Thoron atoms emit particles and radiation and in turn become something else. Uranium is the parent of radium. Several families of radioactive elements, including those of thorium and radium, have been studied in detail and relations between members of the family worked out. Each member emits a characteristic radiation or particle and transmutes itself into a new element. All radioactive elements fit properly into the periodic table.

When a radioactive atom emits an alpha particle, it loses a mass approximately four times that of the hydrogen atom and a positive charge of two units and moves across the periodic table into a column containing elements with similar chemical properties. Loss of a beta particle has little effect on the mass, but negative charge is lost and the atom again alters its chemical properties and moves in the periodic table in a direction opposite to that resulting from loss of an alpha particle.

The end product of each family of disintegration products is lead. All naturally radioactive elements are heavy and have large atomic weights, except potassium and rubidium, which were found by Campbell in 1907 to emit fast beta particles. Light elements do not fit into any of the families of naturally radioactive products.

The disintegration of radioactive elements has provided

means for estimating the age of the earth. By analyzing a sample of uranium ore to determine the percentage of uranium, radium, lead and other products, it is possible on the basis of known rates of decay to compute how long the ore has existed in the solid state. Estimates of the earth's age in this way are much greater than those made by previous methods, and readings of the radioactive clock appear to allow plenty of time for the evolution of human beings as demanded by biologists.

It is probable that radioactivity is responsible for heating the earth's interior, and may also play a part in providing the sun with energy, though this energy is at present ascribed to another process involving what may be called artificial radioactivity.

Radiations from radium, as well as x-rays, are destructive of human and animal tissue and severe burns have been sustained by persons working with radioactive substances. This destructive property has been turned to use in the treatment of cancerous growths, for gamma rays and hard x-rays can penetrate below the surface and destroy malignant tissue. Thus again discoveries in pure science have been turned to practical and beneficial use.

Later chapters will describe in more detail the nature of radioactive processes, a study of which has led to the discovery of artificial radioactivity, transmutation of the elements by laboratory processes, and the release of atomic energy.

Chapter 10

THE RUTHERFORD ATOM

At the stage in the development of physical science with which the present chapter is concerned, a circular development of scientific thought becomes apparent. Thales had believed in a single fundamental cause for all things, a single elemental substance of which all things are made. Later, Democritus taught that matter consists of minute material particles of many kinds, which combine in various ways to produce the objects of the material world. This conception of the ultimate constituents of matter became progressively more definite and the supposed number of ultimate elements more numerous. In the work of Dalton, Avogadro, and their contemporaries ideas of the atom and molecule became exact while the number of ultimate, fundamental and unchangeable elements was reduced to something over eighty in number. The ideas of the alchemists, who sought to change the proportions of the fundamental elements in lead so as to produce gold, became untenable. It was now to appear that the number of truly fundamental constituents of matter was very small; for a time it was believed that these were in fact the electron and the proton or hydrogen nucleus. More recent work has altered this conception, although the number of fundamental components is still regarded as very small. In a sense science has returned to early Greek ideas of the inherent simplicity of nature; at the same time it has become apparent

that the dreams of the alchemists may not have been completely absurd.

The atom of Dalton is the smallest particle into which matter can be divided by chemical means, a statement which is as true today as it was in Dalton's time. The fact that science has succeeded in venturing further, dividing the chemical atom into still smaller parts, results from the advent of entirely new methods.

That the atom could not be as simple as had been supposed was indicated by radioactivity. To be able to emit alpha, beta and gamma radiation with large amounts of energy, the atom must be very complex indeed. Beta particles sometimes emerge with nearly the velocity of light, an extremely high speed for a material particle. It was recognized at once that since alpha and beta particles had come from the inside of the atom, they must have existed in the atom. Whether atoms also contained other constituents remained uncertain, although it became popular to regard the atom as a complex structure consisting of charged components similar to the particles emitted in the radioactive process.

Along such lines J. J. Thomson assumed that each atom consists of a uniform sphere of positive electricity in which small negative charges are embedded. His model answered very well for certain purposes. It explained the presence of the negative charges emitted as beta radiation. It also accounted for the conductivity of ionized gas, for when torn apart the charged portions would move in an electric field and carry electric charge from one point to another. Thomson's model was not of much help with the alpha particle; besides, other facts soon to be discovered demanded the invention of another sort of atom model.

Alpha and beta particles are able to pass through thin sheets of metal, and Lenard had shown that cathode-ray particles will pass through thin aluminum windows. These particles can travel through considerable distances in atmospheric air before complete absorption occurs. But although

Courtesy Westinghouse Electric Co

Mass spectrograph.

the particles may not be stopped by matter placed in their path they will generally be deviated.

The scattering of alpha particles was first noticed by Rutherford in his experiments on the transmission of these particles through air and through metallic foils. The following significant observation was made by him in 1906.

A radioactive source of alpha particles was placed in a box, near one end. At the center of the box was a narrow slit and at the far end a photographic plate. If the box were evacuated, the image of the slit on the plate was clear and sharp, indicating that the alpha particles had travelled along straight lines. But when air was admitted to the apparatus the image became broad and fuzzy, evidence that the alpha particles had been scattered by the air molecules encountered along the way.

Here apparently was a new tool for the physicist. If alpha particles could be scattered by air molecules, they should also be scattered by the atoms in a thin metallic foil, and the observed deviations might give evidence of the arrangement of atoms in the metal; possibly some information on the nature of atoms might be obtained. Neither atoms nor molecules can be seen even with the highest attainable microscopic power; but alpha particles might be sent into matter as messengers, to make inquires as to what was found and to render a report.

Such experiments were performed by Geiger in 1908. Alpha particles journeyed through a strip of metal and were detected by scintillations produced on a zinc sulphide screen. Most of the alpha particles were observed to suffer minor deviations in their paths, which was not surprising in view of Rutherford's observations, and especially if the atoms of metal were constructed according to Thomson's ideas. It was believed that the particles could pass between or even through atoms, being deflected by electric forces whenever they happened to come close to a charged particle in an atom. Under these conditions the deflections would be small. But in the following year Geiger and Marsden noticed that a few of the

scattered particles were deviated through large angles, sometimes greater than a right angle. According to calculations made at this time by Rutherford, something was wrong with Thomson's atom, for cumulative small deflections could not result in such large deviations of so many of the particles.

Rutherford concluded that each large deflection must result from a single encounter. The scattering object must be heavy in order to be able to deflect the heavy alpha particles; electrons are not nearly heavy enough. In order to provide a massive object which might act as a scattering center, Rutherford in 1911 devised a new model for the atom.

Rutherford assumed that each atom contains a nucleus, containing nearly the entire mass of the atom and bearing a positive charge. Around this nucleus was distributed in some manner the negative charge required to render the atom electrically neutral. Negative charges consisted of those observed in cathode rays or beta rays, and these charges occupied part of a spherical volume whose size was that of the atom. The heavy nucleus must be extremely tiny, much smaller than the atom of which it formed the core.

This model of the atom was revolutionary in that it left a relatively large amount of absolutely empty space inside the atom. Incoming alpha particles could penetrate the atom itself and might pass freely through it without causing a disturbance. But if the particle came too close to the nucleus then it would be deflected in its path, repelled by the nuclear charge, and would emerge in a new direction. The scattering of alpha particles observed by Geiger and Marsden was in complete accord with predictions made on the basis of the Rutherford nuclear atom.

Use of the nuclear atom model has led to many scientific triumphs. Besides being a useful tool in the hands of spectroscopists after Bohr had amplified the concept and placed the electrons in orbits around the nucleus, it has forced a revision of thought upon those who regarded the atom as solid and impenetrable.

The theory was amplified by a discovery of Moseley made in 1913, outgrowth of experiments made in the field of x-ray spectroscopy. By a method which is not of immediate concern, Moseley measured the wave lengths of x-rays produced by various elements under the bombardment of cathode rays, and found that as heavier elements were used the x-rays became more penetrating, and shorter in wave length. Characteristic line images in each spectrum were similar for each element, but as the radiating element became heavier, as the atomic weight of the element was increased, each portion of the resulting spectrum was displaced toward the region of shorter wave length. The Moseley diagram, in which the spectra are placed one above another, generally in order of increasing atomic weight, has the appearance of a set of ascending steps.

According to the arrangement of elements in his diagram Moseley assigned to each a number, called the atomic number. Hydrogen, the lightest element, was assigned the number *one.* In contrast to the numbers representing atomic weights these characteristic atomic numbers were integers. Arrangement of the elements in order of increasing atomic number resulted in nearly the same arrangement as occurred in the periodic table of Mendeléjeff. The atomic number, whose significance will presently appear, was in most cases approximately equal to half of the corresponding atomic weight.

By means of experiments on the scattering of alpha-particles it is possible to compute the magnitude of the nuclear charge, assuming that electrical forces between particle and nucleus obey the usual inverse square law of Coulomb. It appeared from such experiments that the nuclear charge was in every case approximately equal to the product obtained by multiplying the electronic charge by one half of the atomic weight of the element in question. As early as 1913, van den Broek advanced the theory that the nuclear charge might in fact be exactly equal to the product of the electronic charge and the atomic number. This idea was tested by Chadwick during the following years and met with great success.

It will be recalled that in the periodic table of the elements certain inconsistencies appeared when elements were arranged according to increasing atomic weight. Arrangement according to atomic number removes these inconsistencies, so that every element takes its place in a column with elements having similar chemical properties, and the atomic number increases steadily as one progresses through the table, whereas the atomic weight occasionally decreases. The atomic number, or net positive charge on the nucleus expressed in terms of the electronic charge, thus assumes an important role in the classification of chemical elements, and is a more sensitive indication of chemical properties than is the atomic weight.

At this point it is necessary to recall a hypothesis of Prout to the effect that all elements are built up from a single constituent which might well be hydrogen. The hypothesis becomes tenable if, accepting the implications of the concept of atomic number, one agrees that heavy atoms consist of the same components as do the lighter ones, including hydrogen. The picture is not quite as simple as was at first supposed. It was thought for a time that atomic nuclei consist of a combination of protons (hydrogen nuclei) and electrons. The hydrogen atom contains one proton as a nucleus, and one extranuclear electron. The next heavier atom, that of helium, was supposed to contain a nucleus in which four protons were combined with two electrons to produce the required mass of four units and charge of two units; this atom in the neutral state would have two extranuclear electrons. Thus all atoms were constructed from the same elemental constituents.

One serious difficulty with the foregoing theory was that atomic numbers are integers, whereas atomic weights are not. This difficulty was removed when it was found that various atoms of the same chemical element might not have identical weights. The majority of the elements have isotopes, atoms of the same atomic number but different atomic weights; atoms having the same atomic number can not be separated

from each other by chemical means. The measured atomic weight of a chemical element is the average of all atomic weights present, with due regard to the relative numbers of atoms of each isotope in the sample.

The existence of isotopes was discovered in the study of families of the radioactive elements. If, for example, an atom loses an alpha particle, its nucleus loses a mass of four units on the atomic scale, and a positive charge of two units, and it becomes an atom of a different chemical element. The final product of each radioactive family has the same atomic number as lead, and for all chemical purposes is lead, but the respective atomic weights were not those usually associated with lead. If these atoms were present in a sample of lead, the atomic weight would be altered by their presence to an extent depending on the relative proportion of each.

Pioneer work on isotopes has been done by Aston, as well as by Thomson and by Dempster, using an instrument called a mass spectrograph in which atoms are sorted out according to their mass. A stream of charged molecules is produced in some manner, generally by passing an electrical discharge through material in the gaseous state and drawing the resulting ions through a vacuum chamber by means of an applied electric field. Narrow slits or holes provide a thin parallel beam of particles. The stream of particles is first deflected by a transverse electric field, then passes through a magnetic field arranged to produce deflection in the opposite direction. Heavy ions are not deflected as much as the lighter ones and the various streams of ions, separated now according to their respective weights, fall at various spots upon a photographic plate. Atoms which were chemically inseparable have thus been separated by physical means. Although the mass spectrograph has been invaluable, other physical means exist for the separation of isotopes, a number of which were used in the preparation of material for the atomic bomb.

One of the great triumphs of atomic theory built upon Rutherford's nuclear atom has been the artificial disintegra-

tion and transmutation of the elements. If the chemical property of an atom depends on the charge and structure of its nucleus, and if the constituents of the nucleus are simple and few in number, it should be possible to alter the structure of existing nuclei by adding or subtracting components, thus changing the chemical nature of the atom. In this new field Rutherford was again the pioneer. He had been engaged in studying the passage of alpha particles through gases. In the case of hydrogen, an alpha particle would occasionally hit a molecule and give it so much energy and high speed that a hydrogen particle would be produced, travelling much farther than could the alpha particle itself. When nitrogen was used, long-range protons were again observed, particles which could travel long distances because their small relative mass allowed little loss of momentum or energy in intermolecular impacts. Here the inference was inescapable that hydrogen nuclei had been knocked out of nitrogen atoms by the impact of the alpha particle. After suffering such a collision, the struck atom could no longer be a nitrogen atom, since it had lost at least one of its component parts. The effect of transmutation could not be observed in oxygen and some other gases, but certain solids, including boron, sodium, and sulphur gave successful results. In these experiments the number of atoms actually disintegrated was far too small to detect chemically, though later (this was in 1919) transmutation has been carried on to an extent allowing chemical separation of the products.

More recent experiments, principally by Brackett and also Harkins, have been strikingly successful. These investigators used a method of detection developed by C. T. R. Wilson about 1911, which depends on the fact that when moist air is suddenly cooled by expansion some of the moisture will condense and become visible as a cloud. Wilson arranged a cylinder with a piston which could be suddenly lowered, producing expansion and cooling of the enclosed gas. Under these conditions moisture will condense on dust particles, and also on ions. The tracks of alpha particles through air can be made

plainly visible by expanding the gas just after a particle has plowed among the molecules, knocking them apart and leaving a trail of ions upon which moisture condenses.

Alpha particles leave tracks which are generally straight, but often exhibit bends and kinks near the end of the trail where the particle has been slowed down sufficiently to suffer deflection in a collision with an atomic nucleus. Paths of beta particles can also be observed but, because of the light weight of the particles in comparison with atomic nuclei, their tracks are not nearly as strong or straight as are those of alpha particles.

When an alpha particle is deflected by a nucleus which is not too heavy, the nucleus recoils under the impact and the fog track is Y-shaped, showing not only the original path of the particle but also its path after deflection as well as that of the struck nucleus. If anything is knocked out of the nucleus, the path of this debris can also be observed. The length and strength of each path enables the computation of the mass of the particle concerned and one can tell whether the nucleus has really been altered. Sometimes the alpha particle is absorbed by the nucleus with the ejection of a proton. This is transmutation.

A few years ago it would have been exact to say that few atoms had ever undergone transmutation and that the yield obtained from such experiments was tiny indeed. Large amounts of energy are required to disrupt the nucleus, and alpha particles supply this energy in a convenient form. But no longer are the unstable nuclei of radioactive elements the only source of energy needed for the transmutation of elements, and transmutation in the laboratory of nearly all the elements has not only increased scientific knowledge, making possible, among other things, the large scale release of atomic energy; new elements have been produced, elements which temporarily possess radioactive properties of use in biological research and cancer therapy. Radium can not be left in the human body without disastrous results, but table salt or some

other common substance made temporarily active may be injected, since it loses its activity in a comparatively short time. Biology and medicine have gained by the use of temporarily active substances as tracers; in attempts to find out how the body uses certain chemical elements, these may be activated and included in diet. The advantage of the method lies in the fact that distribution and disposal of the material can be accurately traced, inasmuch as the radioactivity of the atoms allows a very few of them to be detected, even through skin or other tissue, whereas chemical methods require samples containing many atoms or molecules. Moreover, molecules not eliminated will soon lose their activity and do no harm.

Many transmutations have become routine laboratory or even production processes. The story of the development of these processes and techniques, as well as an account of their operation, will appear in future chapters.

Chapter 11

THE QUANTUM THEORY

THE OPENING YEARS of the present century have witnessed a number of significant discoveries, many of such a radical nature as to alter the trend of scientific thought. Several of these discoveries have already been noted. The theory of light, dormant since the time of Fresnel, was also undergoing revolutionary changes in which the pure form of the wave theory was to be discarded in favor of the modern corpuscular theory of radiation. When Max Planck had resolved difficulties in the theory of heat radiation by the invention of the quantum of action, and Einstein had injected the idea of the light quantum or photon, the world of science was faced with a choice between wave theory and corpuscular theory, which has finally resulted in a combination of both.

Lest the reader be terrified by the very name of the quantum theory, it is necessary to state what a quantum is and what a quantum theory must be.

A quantum is a certain definite amount of something. The cent is a definite amount of money and could be called a quantum of money. As generally used, the word quantum signifies an ultimate unit which can not be divided. In computing a bank balance, the total credit or debit is always found to contain an integral number of cents. The chemical theory of matter is really a quantum theory: a sample of iron, for instance, always contains an integral number of iron atoms. The atom was formerly regarded as indivisible, as indeed it still is when

treated chemically, and the existence of three-quarters of an iron atom was unthinkable. One might also speak of a quantum theory of humanity, since the population of a city always contains a whole number of individuals.

In contrast to a quantum theory one thinks of something that is essentially continuous. Distance is continuous. If one person takes three thousand steps in walking a mile, another may take five thousand, and a child will take more; the distance is divisible into units as small as desired, without limit.

The quantum theory of modern physics is principally concerned with energy and a related quantity called action. Action, as physically defined, is obtained by multiplying energy and time. If ten units of energy are used or released in five seconds, then fifty units of action are involved. The term action is not to be confused with the familiar word of everyday speech used, for example, in speaking of the action or mode of operation of a steam engine. It is unfortunate that the physical definition of action has no counterpart in general usage; if it did, the concept would be easier to grasp.

The quantum theory is the modern theory of radiation; it has forced into the category of discarded beliefs one of the most fundamental and firmly founded of scientific conceptions —that heat and light are emitted, absorbed, and propagated in a continuous manner. Nothing less than the most secure experimental facts could have produced such a revolution, for nothing in nature is more real than a carefully obtained experimental result. Facts however require interpretation, and new facts produce new theories. But always the theoretical interpretation must make sense and not lead to predictions that are experimentally absurd. Although a mass of experimental observations have been interpreted on the assumption that light is emitted continuously from a source, with trains of spherical waves spreading out in all directions, new observations have forced the acceptance of the quantum theory in which light is regarded as a stream of small bunches of energy which move through space along straight lines and act for all

the world as if they were small material particles. The solution of questions raised by the new theory has occupied the attention of scientists for most of the present century.

Max Planck, author of the quantum theory, was over forty years old when in 1900 the theory was born. Planck had been interested in thermodynamics, especially as applied to the laws of heat radiation. Kirchhoff and Bunsen had studied the spectra of various elements, and in 1859 Kirchhoff had noticed that the radiation from what is called a black body depends only on the temperature to which it is raised, and not at all on the nature of the body.

Objects are black when they absorb all incident light. Colored objects appear so because their surfaces reflect certain of the wave lengths present in the incident light and absorb others. The surface of a perfectly black body, if such could be prepared, is perfectly absorbing as contrasted to the surface of an ideal mirror which can absorb no radiation whatever. Blackening the bulb of a thermometer exposed to sunlight will result in more complete absorption and a higher indicated temperature than before application of the black coating.

Kirchhoff discovered that besides absorbing more radiation than others when cool, black bodies emit more radiation than others when heated to incandescence.

A perfectly black body is not easy to prepare and, in any case, the surface would be altered or destroyed at high temperatures. The laboratory black body, which has for experimental purposes all the desired attributes of the ideal absorber, consists of a hollow space or enclosure provided with a single small opening. The enclosure is placed inside a furnace so that the cavity can be heated and maintained at any desired temperature.

That this apparatus acts like an ideal black body can be seen when it is realized that radiation entering the cavity through the small opening has very little chance of getting out again. Such radiation, once it gets inside, will be reflected

back and forth, some being absorbed at each reflection; it will probably be completely absorbed before by chance it finds itself directed outward through the opening. If however enough radiation gets in, the cavity becomes heated and emits radiation of its own, of a character and intensity depending only on the temperature inside the cavity, and not on the material lining the cavity. This is true to such an extent that after temperature equilibrium has been reached, objects inside the cavity, as observed through the opening, become indistinguishable from each other and from the general background illumination.

Of particular interest in the study of radiation from an ideal radiator is the spectral distribution of emitted energy: how is the energy distributed among the various wave lengths in the spectrum, and at what wave length is most of the energy emitted? In general the curve obtained by plotting along a vertical axis the amount of energy emitted in a narrow wave length range, and along a horizontal axis the wave length of each range, resembles a gently sloping hill. The height of the hill at any point indicates the intensity of radiation emitted at a particular wave length.

The shape of the radiation curve depends only on the temperature. If the emitting source is heated to a dull red, the hill is low and may have its peak in the invisible infrared wave length region. At higher temperatures the hill becomes higher and the peak moves into the visible region and then toward the blue end of the spectrum, corresponding to shorter and shorter wave lengths. As a matter of fact, as was shown by Wien in 1893, the product obtained by multiplying the absolute temperature of the source by the wave length for the peak of the corresponding radiation curve turns out to be a constant; this relation is true for all temperatures, provided the source has the attributes of an ideal black body.

Attempts had been made to predict the form of the energy-wave length curve, that is, to derive an equation for the curve on the basis of reasonable assumptions regarding the nature

of the source and of the emission process. The experimental curves had been well established through the work of Paschen, Lummer and Pringsheim, Rubens, Kurlbaum and others. Calculations had been made by Wien and by Rayleigh. The theories seemed correct and the experiments left little to be desired—but the two did not appear to meet. Paschen showed that the predictions of Wien were in agreement with the experimental curve at the violet end of the spectrum, while Rayleigh's theory was shown by Rubens and Kurlbaum to be verified in the red region. No theory would account for the shape of the radiation curve over its entire wave length range.

Planck was interested in these attempts to explain the shape of the radiation curve. It had become apparent that when the correct theory were at last obtained, this theory should contain a function or quantity independent of the nature of the radiating source, a universal function—for the form of the radiation curve had been found to depend only on temperature and not on the nature of the source so long as the latter was a perfect emitter. Planck proceeded to search for this universal function.

Before deriving a radiation law it is necessary to make assumptions regarding the nature of the source. The source chosen by Planck was simple and appeared ideal for mathematical manipulation: the Hertzian linear oscillator.

The linear oscillator may be thought of as an electric charge, or a pair of such charges, oscillating back and forth through a position of equilibrium under forces of an elastic nature, and emitting electromagnetic radiation. Planck imagined that the cavity of an experimental black body was filled with linear oscillators; radiation emitted by the oscillators would eventually fill the cavity and reach equilibrium at some definite temperature, whereupon it should become possible to calculate the spectral distribution of radiant energy present in the cavity and emitted from the opening. In equilibrium radiation would be both absorbed and emitted by each oscillator. It was assumed that the oscillators were the only source

of radiation, for the cavity was supposed to have perfectly reflecting walls and to contain no other substance.

The laws governing radiation from a simple linear oscillator were known or, rather, Planck believed that they were known. Once the theory of the oscillators in the cavity had been worked out, it was believed that the same laws would apply to radiation from any perfect radiator and would contain the universal function which was sought.

Planck used at first the methods of thermodynamics, which apply to equilibrium conditions. He was aided by the advice of Boltzmann, who had applied the theory of probabilities to studies of heat and had considered the relative probability of various equilibrium conditions. After Boltzmann had introduced the concept of probability into thermodynamics the latter was allied more closely to the newer statistical mechanics. Boltzmann is also remembered for contributions to the kinetic theory of gases, especially relating to the distribution of molecular velocities studied by Maxwell.

At first Planck resorted to what was regarded as merely a mathematical artifice. He assumed that radiant energy was emitted by his ideal oscillators in separate small but definite amounts. Though the emission process was thus initially regarded as discontinuous, he did not believe the whole story had been told; the assumption was a preliminary one, making possible calculations on the probability of emission. He would proceed to decrease the size of the units so that in the limit the laws governing continuous emission of energy might be obtained.

At this point things began to happen. Initial calculations fitted the experimental facts very closely, and agreement was obtained with the entire radiation curve. But on integrating the equations, allowing the size of the assumed units of emitted energy to decrease without limit, his predictions ceased to be valid except in the region of long wave lengths, the red end of the spectrum. Agreement of this sort had been attained before in the theory of Rayleigh. Something better

was needed, and it began to look as though his mathematical artifice had contained more of reality than he had supposed. Although it was difficult to believe that radiation could be emitted discontinuously, all the facts pointed in that direction. As a result of this unexpected impasse the quantum theory came into being.

Planck's radiation law contains two constants. One is called Boltzmann's constant, a quantity playing an important part in kinetic theory and related to the kinetic energy of a single atom or molecule; it is also related in a complex manner with quantities including the mass of the hydrogen atom and the electronic charge, and knowledge of its magnitude enabled early and fairly accurate estimates of the charge on the electron. The second constant appeared in Planck's theory for the first time, a constant value of the physical quantity called action.

The constant discovered by Planck, called by him the elementary quantum, or quantity of action, is now universally referred to as Planck's constant and denoted by the symbol h.

The essence of the quantum theory of heat radiation as presented by Planck is that heat radiation is emitted and absorbed, not continuously, but in discrete units one at a time. The amount of energy in each unit is given by the product of the universal constant h and the frequency of the radiation.

The new theory contained ideas which were too revolutionary to allow its immediate acceptance. It was to make its way slowly and persistently until at last nearly every branch of physics was forced to accept it. One of the first to recognize the importance of the new ideas was Einstein, who in 1905 accepted the idea of discontinuous emission and assumed that after emission the energy remained in discrete units called light quanta or photons, and made predictions of fundamental importance regarding the emission of electrons from metals under the action of light in the photoelectric effect. These predictions were verified in the experiments of Millikan performed in 1916, which will be mentioned later in the book.

In 1907 Einstein brought the quantum theory to bear on the theory of specific heats. Believing that the heat energy of a solid body consists essentially of the energy of vibration of the atoms present, Einstein assumed that vibrating atoms were limited in their modes of vibration in accordance with quantum rules: certain modes of vibration were not to be allowed, nor were certain values of vibrational energy, with the result that vibrating atoms must pass suddenly and without continuous transition from one energy state to another. For the first time this theory was able to explain the peculiar behavior of the specific heat of diamond and other substances at very low temperatures whose measured values were far lower at these temperatures than could be accounted for by any previous assumption. Work along this line was carried on by others, principally Debye.

The quantum theory of Planck has had many triumphs. Included among these is the Bohr theory of the planetary atom and the resulting theory of spectroscopy, with which the following chapter is concerned.

Chapter 12

SPECTROSCOPY AND THE BOHR ATOM

The Bohr theory of atomic structure, one of several applications of the fundamental discoveries of Planck and Einstein, was published in 1913.

Development and application of these basic discoveries in the quantum theory have occurred simultaneously along a number of lines. Although postulates made in 1905 by Einstein are essential to the formulation of Bohr's theory, the latter received immediate experimental justification, whereas proof of Einstein's photoelectric equation had to wait until 1916. For this reason, and also because spectrum analysis is much older than any knowledge of photoelectricity, the theory of Einstein will be mentioned only briefly at this point. Millikan's experiments on photoelectricity, as well as those of A. H. Compton in a related field, were soon to produce conclusive evidence for the existence of the light quantum or photon and the validity of the new corpuscular theory of radiation.

The discovery that electrons are ejected from a metallic surface by the action of incident light rays or x-rays was made shortly after the discovery of x-rays themselves. Indeed the two discoveries are related and were bound to come closely together. X-rays are produced by the impact of cathode-ray particles or electrons on matter, while electrons are ejected from matter exposed to x-rays. Lenard had studied the ejection of electrons from metals by ordinary visible light, and Barkla as well as Whiddington had made similar observations

while working with x-rays. It was known in general that the velocity of the ejected electrons depends, not as might be expected, on the intensity of the incident radiation, but rather on the wave length or frequency. Blue light has a higher frequency and a shorter wave length than red light; x-rays have even a higher frequency. Among x-rays, those of higher frequency are more penetrating than those whose frequency is lower, or whose wave length is longer.

The speed of photoelectrons increases steadily as the frequency of incident radiation is increased. The number of photoelectrons obtained depends however on the intensity of illumination, the brightness of the incident light. Conversely, the frequency of x-radiation produced when cathode-ray particles strike a target depends directly on the speed of the incident particles: faster particles produce more penetrating x-radiation of higher frequency than do slower particles.

Einstein had these facts, as well as the quantum theory of Planck, at his disposal. His theory of the photoelectric effect, published in 1905 and verified a little over ten years later, showed evidence of the powerful intuition and lack of prejudice which has characterized all of his work.

Planck had discovered discontinuous emission and absorption. Einstein went farther, and assumed that after emission a quantum of radiant energy remains intact, and travels through space somewhat like a particle. The invention of the light quantum, the corpuscle now called the photon, was of course completely at variance with ideas inherent in the older wave theory, which still was in good repute. But other difficulties were at one bold stroke removed, principally that relating to the energy of ejection of a photoelectron.

Electrons are ejected as soon as radiation meets the metal surface, with more energy than they could possibly absorb from a wave front, unless they collected the entire energy of all parts of the wave, which is impossible, since parts of the wave are travelling in quite different directions. An alternate hypothesis, that the energy of ejection comes from the

atom and is merely released by the light, is not compatible with the observation that the electron's energy depends on the kind of light, not the kind of atom. It appeared that energy in incident radiation must be concentrated so that the energy of one such concentration suffices to eject one electron. Even if atoms were able to store energy from a wave front, the immediate ejection of the electrons made this view untenable.

Einstein chose the hypothesis which seemed simplest to him; in spite of almost universal belief in the wave theory, he assumed that energy in a beam of radiation is concentrated in the form of light quanta, one of which is able, when absorbed, to cause the emission of a photoelectron. His equation is expressed in the rather simple form: $E = \frac{1}{2}mv^2 = hf - W$. In the equation, E is the kinetic energy of a photoelectron of mass m and velocity v; h is Planck's constant, f is the frequency of the radiation, and W is the amount of work needed to pull the electron out of the metal and away from the surface.

Einstein's photoelectric equation, when expressed in words, states that the kinetic energy of a photoelectron is equal to the energy of an absorbed light quantum less the amount of energy required to free this electron from the metal surface. At the time, the most exciting part of the equation was the term hf, product of the universal constant of Planck and the frequency of the radiation. This product is the energy of a single light corpuscle, since energy is action divided by time; frequency is the reciprocal of the time need for one vibration in a light wave. Einstein thus retained the concept of periodicity in light, which in fact has never been removed, while suggesting that light waves, if they exist, must surely be of a different nature than had been supposed. A similar equation, without the work function, applies to the production of x-rays: in this case v is the velocity of incident electrons and f is the frequency of the x-rays which are produced.

In work to be described later, Millikan not only verified the

equation but obtained a very exact measurement of the fundamental quantity h, the elementary quantum of action.

In 1913, when Niels Bohr was less than thirty years old, the quantum theory of radiation had been found to describe the spectral distribution of heat radiation, and the concept of the light quantum had been introduced without widespread acceptance. Radioactivity had led to the Rutherford nuclear model of the atom, consisting of a massive, positively charged nucleus surrounded by electrons whose number in the neutral atom was equal to the number of electronic charges on the nucleus. Components of the atom were very small, so that the atom was mostly empty space. Spectrum analysis had been studied for years, and it was recognized that a completely successful model of the atom would have to account for production of the known spectra of the elements.

Bohr started out with modifications of the Rutherford atom. It was known that electrons surround the nucleus; Bohr assumed these electrons to move around the nucleus in circular orbits, subject to the well known laws of dynamics applying to planetary motion. The electrical force of attraction between electron and nucleus was balanced by centrifugal force. Bohr's atom thus had the aspect of a miniature solar system in which the nucleus played the role of the sun, and the electrons that of the planets.

In devising this model of the atom Bohr had a particular aim in mind: he was trying to evolve a theory which would account for the wave lengths of light observed in optical spectra, particularly the rather simple spectrum of hydrogen. An obvious step at this time would have been to retain completely the ordinary laws of dynamics and to assume that the electron in the hydrogen atom moved around the nucleus in an orbit whose size continually decreased under the action of central acceleration as the electron radiated energy. For it was believed that an accelerated electron must radiate, and an orbital electron is accelerated always toward the central point of attraction. Under these conditions the frequency of the

radiation should be the same as that of the accelerated or orbital electron. But this obvious step was not made, and for an excellent reason: Such assumptions would not provide a theory which could be made to agree with observations. By including assumptions based on the new quantum theory, Bohr hoped to attain a model of the atom that would enable prediction of wave lengths actually observed in spectrum analysis.

It often happens that a scientific hypothesis seems completely absurd and yet leads to significant conclusions. Such was the case with Bohr's assumptions regarding electronic orbits. He assumed that an electron might move around in an orbit of fixed size for a considerable time without radiating energy or falling in toward the nucleus. Luckily he did not have to explain this departure from current belief, but merely wondered what would happen if such were the case. He further assumed, in defiance of previous knowledge, that only a few of the infinity of orbits defined by classical dynamics were available to the electron, and that after a time spent in one such orbit the electron would make some sudden sort of transition into another. The electron was allowed to radiate only during its jump from one stable orbit to another. The frequency of emitted radiation was not supposed to depend on the orbital frequency of the electron, as older ideas would have it, but rather on the energy possessed by the electron in each orbit. Specifically, if E_1 and E_2 represent the energy possessed by the electron in two of the allowed orbits, then the frequency emitted when the electron jumps from the second orbit to the first is given by the expression: $hf = E_2 - E_1$.

The quantum theory was thus injected into the theory of atomic structure. Orbits available for the electron were those in which the angular momentum * of the electron would be equal to $nh/2\pi$, where n is a small integer.

* Linear momentum is the product of mass and velocity, mv. Angular momentum, or moment of momentum, mvr, involves also the radius of the path in which the mass is moving. The quantity π (pi) is the ratio of the circumference of a circle to its diameter.

The radical nature of Bohr's assumptions were recognized at once. No explanation was given as to why they should be true or what they really meant. Their use would be justified if they led to predictions in agreement with experiment, in which case they would be accepted as valid, whether understandable or not. Science is that way about hypotheses. These particular assumptions were soon found to be valid; with a knowledge of the mass and charge of the electron as well as of the hydrogen nucleus, or proton, Bohr's hypotheses enabled him to predict with accuracy the wave lengths occurring in the hydrogen spectrum.

Since the work of Kirchhoff and Bunsen in 1859, it had been known that the various elements give characteristic spectra, including light of different wave lengths and intensities. The spectrum of a glowing gas exhibits a number of thin lines, each an image of the slit through which light enters the instrument. These lines are distributed in various ways in the spectrum according to their wave length or color; the color sequence is the same as that of the rainbow, though in many cases certain colors are absent. The visible spectrum of sodium gas contains two yellow lines, very close together, and nothing else, while other gases give spectra containing many lines distributed throughout the visible spectral region. Kirchhoff and Bunsen had shown that by making a catalog of the spectra of elements, a sample could be analyzed by heating the material and comparing the resulting spectrum with those in the catalog. The method works even though a number of elements are present in the sample. Such a method of analysis is entirely empirical, for there was no theory regarding the ultimate source of the particular wave lengths observed.

The situation was slightly clarified in 1885 when Balmer attempted an analysis of the spectrum of hydrogen. He measured the wave lengths in this spectrum and found a simple numerical relationship between the frequencies of light responsible for production of the various line images in the spectrum. Wave lengths could be obtained from the formula,

since frequency and wave length have a simple relation to each other. Balmer's formula for frequencies in the hydrogen spectrum may be written: $f = R\ (1/m^2 - 1/n^2)$ where R is a constant and m and n are integers. Later Rydberg noticed that the constant was applicable to the spectra of a number of elements, and for this reason the constant is now called Rydberg's constant.

An equation of such simple form is always provocative, especially if it has resulted from empirical observations rather than theoretical deductions. It looks as though it should be obtainable from a theory based upon rather simple assumptions if these could only be found.

Bohr used his theory of the hydrogen atom to compute the wave lengths to be expected in the hydrogen spectrum. His calculations gave not only the correct wave lengths, but also a formula similar to that of Balmer. The constant R was found to contain the well known physical constants, the mass and charge of the electron, as well as Planck's universal constant h. Here was indeed a triumph for the quantum theory.

The two terms in the formula of Bohr, and of Balmer, are proportional to the energy possessed by an electron in each of the two orbits concerned in a particular electron transition, the difference in these energies being equal to the frequency of the radiation multiplied by Planck's constant. The integers m and n are called quantum numbers.

Since in the expression obtained for the radius of an orbit the squares of the quantum numbers enter, the orbits in which the electron is allowed to move increase in size in proportion to the squares of small integers: one, four, nine, and so on. Spectrum lines in the Balmer series correspond to electronic jumps from outer orbits into the second innermost orbit. If radiation is absorbed by hydrogen gas, the only radiation absorbed will have wave lengths and frequencies which the gas could itself emit; in the absorption process, electrons make sudden transitions from the second to outer orbits under the same rules as apply when radiation is emitted, except that

now the electron is moving into larger orbits of higher energy. In either process, emission or absorption, an entire quantum must be involved, otherwise nothing happens. A similar situation applies in the photoelectric effect, although in this case the probability for the absorption of any light quantum whose frequency lies above a certain limit is pretty large; however, if any action at all takes place an entire quantum must be absorbed.

Besides the Balmer series of spectrum lines in the visible region, other spectrum series were predicted by the Bohr theory, notably the Lyman series in the ultraviolet corresponding to electron jumps into the innermost or one-quantum orbit; and the Paschen series in the infrared region, with electron transitions into the three-quantum orbit.

Bohr further predicted a similarity between the hydrogen spectrum and that of ionized helium. The ionized atom of helium contains a nucleus around which a single electron circulates; in the ionization process one of the electrons normally present has been torn away. This atom is similar to the hydrogen atom, except that the nucleus, which is in fact the alpha particle of radioactivity, is heavier and carries a double charge—differences which would be expected to alter the spectrum somewhat. The spectra are so similar that Pickering and Fowler had erroneously ascribed the spectrum of ionized helium to the hydrogen atom. Bohr's theory, from which wave lengths in both spectra could be calculated, cleared up the difficulty and experiments of improved accuracy showed the distinctness of the two spectra.

The theory of Niels Bohr had many successes but it was found to leave certain facts unexplained. In 1915 Sommerfeld, whose books on atomic structure and spectroscopy have been standard reference works for years, introduced elliptical orbits into the Bohr atom. Since the velocity of a body in an elliptical orbit is not constant, it became necessary to include the relativistic change in mass with change in velocity, with the result that in many cases the predicted spectrum line be-

came in reality a number of closely spaced lines. This fine structure, as it was called, is observable when the resolving power of a spectroscope is increased.

Bohr's theory persisted with only minor additions and refinements until about 1925, at which time major changes became necessary. It has supplied much information concerning the structure of atoms of the various elements, and aided in the search for regularities in the corresponding spectra. Theories of spectra and of atomic structure have developed hand in hand, each aiding the progress of the other and furnishing clues as to which lines of investigation might be productive. The usefulness of the theory has not been confined to optical spectra, but has as well aided discovery in the x-ray region.

In 1911 Laue discovered a method of measuring the wave lengths of x-radiation. X-rays are not deviated by glass prisms and recourse must be had to other methods.

The diffraction grating is widely used in optical spectroscopy. Its operation is not unlike that of the double source in Young's famous experiment, except that instead of two slits there are many parallel lines, five or ten thousand or more to the inch, ruled on a glass or metal surface. With more openings or reflecting spaces, the intensity of the image is greater and the resolving power is increased. The American physicist Rowland was a pioneer in the construction of excellent diffraction gratings, and the accuracy of his measurement of wave lengths in the solar spectrum was not surpassed for years.

Although x-ray wave lengths could be calculated by the quantum equation of Einstein which was first developed for the photoelectric effect, it was desirable to obtain measurements of these wave lengths. Laue reasoned that the atoms in a crystal might serve as a diffraction grating. These atoms are regularly spaced by distances appropriate for measurement of the short x-ray waves. X-rays scattered by atoms might interfere with each other and present an interference

pattern giving information regarding not only the wave lengths of the rays but also the arrangement and spacing of atoms in the crystal.

First it was necessary to assume the crystal structure. Rocksalt has a cubical crystal structure of great regularity. From a knowledge of the density of the crystal and the number of atoms in a gram-atom of rocksalt it is possible to determine the interatomic distances in the crystal.

Laue obtained a sort of spectrum, consisting not of the usual lines but instead a symmetrical series of spots spaced around the position of the central or undefracted image. Powdered crystal produced a pattern of concentric circular rings. Knowledge of the atomic spacing in the crystal enabled him to calculate the wave lengths of the rays, which turned out to be much shorter than any wave length occurring in visible light. A similar procedure has been applied to the even shorter wave lengths present in gamma radiation. With a knowledge of x-ray wave lengths, x-rays become a powerful means for investigating the structure of crystalline material of all sorts. Much work along this line has been done by the Braggs, in England.

Certain discoveries of Moseley in the x-ray field have already been noted. Characteristic x-radiation from the various elements as observed by Moseley was found to fit well into the Bohr theory. In the production of x-rays, electrons in the inner portions of complex atoms, near the nucleus, were concerned in contrast to the production of optical spectra by outer electrons. Inner electrons are in a stronger force field because of their proximity to the nucleus; for these electrons the orbital energies are larger and the emitted frequencies greater. It may be noted that outer electrons play an important role in providing the forces responsible for chemical combination of atoms into molecules.

The quantum theory of spectroscopy, originally developed for atoms, has been extended into the field of molecular spectroscopy. A molecule can rotate as a whole, or the constitu-

ent parts can vibrate with respect to each other. The electrons may also change from one energy level to another. In each case there is a quantum rule which decides which modes of rotation, vibration, or electron transition are to be allowed. The frequency of radiation emitted is always given by Bohr's rule, derived from the earlier assumption of Einstein: The frequency of the radiation, multiplied by Planck's constant, is equal to the difference in energy of the radiator in the initial and final states.

In order to retain agreement with experimental observations it has been necessary to impose certain restrictions on the way in which electrons can jump from one orbit to another, or molecules change their state. In many cases it has been difficult to give any reason for these selection rules, except the important reason that by their use the theory can be made to fit the facts and forbid the production of spectrum lines which are never observed.

A further principle was enunciated by Bohr on the basis of experimental observations, the very useful principle of correspondence. When the quantum number is large and electrons are in the outermost orbits of an atom, classical laws are obeyed and quantum laws approximate the older principles. Under these conditions quantum orbits are large and close together; in running down from one orbit to another the electron spirals in toward the nucleus in much the same way as predicted by older theories. Also, since the emitted frequency is in any case a sort of median between the frequency of the electron in the two orbits concerned, for higher quantum numbers and correspondingly large orbits the frequency of radiation becomes nearly equal to the orbital frequency of the electron. The principle of correspondence has been used in several attempts to reconcile the older classical theories with the quantum theory but, as will appear, such reconciliation as is possible has come rather unexpectedly from another direction.

Chapter 13

THE EXPERIMENTAL BASIS OF RELATIVITY

THE GREAT advances made by science during the past few decades have been characterized by the extension of scientific experience into new regions. Investigators have been able to make more refined and delicate astronomical measurements and to peer farther and farther into the depths of space; they have learned how to look more deeply into the structure of matter, even into the minute confines of the atom. Instead of sense impressions, the dial readings of scientific instruments generally are used to impart information.

The parting of the ways, the separation of the world of scientific experience from the ordinary world of sense experience, was foreshadowed by the discovery of the chemical atom, which could only be experienced by scientific methods. Separation became more complete in the discovery by Rutherford of the great amount of empty space inside the atom and thus inside all material objects. Human senses give certain information about the world; the experiments of science often supply quite different information. Apparently the two points of view must be kept separate, and questions concerning reality qualified by the realization that the world appears differently when viewed in different ways. Should a metal coin be considered as a solid object or rather as a loose assemblage of particles separated by considerable distances?

The ideas of scientists are ruled by the progress of experi-

ment. The impetus received by physical science at the turn of the century derives from advances in experimental technique as well as the increasing accumulation of scientific fact. Scientists must be forgiven if, as has happened a number of times, they force a general revision of ideas. They are doing their best to discover for the rest of us the secrets of nature, whether these secrets are of particular interest in the world of ideas or are to be of practical importance in the more or less immediate future.

The exalted position of experimental evidence appears to good advantage in the circumstances attending the advent of relativity. A great deal of accepted theory had to be thrown overboard, together with a number of concepts. The discarded theories had claimed a validity which was not theirs: Founded originally upon experiment, generalizations had been made which were not demanded by the very experiments on which they were based. An immense gain in simplicity and plausibility followed the rejection of geocentric cosmology in favor of the Copernican system. Einstein's rejection of outmoded theories and concepts has done the same good turn for modern science.

The frontiers are still expanding. It is probably too much to expect that knowledge obtained in regions of experience which have never before been fathomed, should agree with notions of reality gained from objects near in both space and time, and comparable in size to a human being.

The theory of relativity is generaly identified with the name of Albert Einstein. As it exists today the theory represents the work of many scientists and involves both theoretical and experimental investigation; but it was Einstein who made the fundamental postulates, and showed the importance and fundamental nature of the new viewpoint. He saw the necessity for a new way of looking at things, and has upset not only the mode of scientific thought but as well the thought of the entire world. His idea has been that if a fact requires too much explanation, this fact may have been regarded in the

wrong light; possibly an attempt is being made to explain away something that simply doesn't exist.

Einstein's first paper on relativity was published in 1905, the same year in which he presented his theory of the photoelectric effect. He was twenty-six at the time, had been a student in Switzerland, and was employed in a German patent office. It is interesting, in the light of his lonely support of Planck's quantum theory, that for a number of years Planck was among the very few to espouse the new theory of relativity.

Any historical discussion of relativity must start in the year 1881 with the famous experiment of Michelson and Morley.

The wave theory of light had demanded the existence of a medium in which light waves might travel. The later work of Faraday seemed to require a medium in which lines of electric and magnetic force could exist. When Maxwell published his theory of the electromagnetic field, and it became apparent that light waves were electromagnetic in nature, the position of the hypothetical ether was well nigh impregnable. Objections, however, had been raised. The ether was required to have inconsistent properties: It must be an elastic solid in order to allow the propagation of transverse waves, but it had to be so tenuous as not to interfere with the motion of the planets. The ether concept was perhaps aided by the advent of Rutherford's atom, which was so porous that the ether could flow freely through matter, but pressure of a different sort was being brought to bear. Already topheavy because of the multitudinous demands made upon it, the concept of the ether was to succumb from two causes: It toppled under its own weight at the same time that the underpinning was removed. Its disappearance was well timed, for it had become so filled with stresses and strains and all sorts of imagined mechanisms that scientists would have had a difficult time in making any further demands upon it.

In 1881 however it was believed that the earth was moving

through the ether, and that an ether wind was blowing through laboratories and even through the scientists themselves. Michelson and Morley decided to look for evidence of this wind.

Imagine that someone is swimming in a stream. If he swims upstream he will make less progress along the shore than if he swims downstream. He may decide to swim across the stream, but if he wants to reach the shore opposite his starting point he will have to head at an angle upstream and swim a greater distance than actually separates the banks. He may think that he can swim upstream and back a distance of a hundred yards in the same time it takes him to swim the same distance across the stream and back, but if so he is mistaken and will discover his error when he makes the trial.

In the experiment of Michelson and Morley, a light beam plays the part of the swimmer, the ether that of the stream. Light is supposed to be moving in the ether. The velocity of the ether stream depends on the various motions of the earth, so that rotation and orbital revolution combine to make the ether wind fast or slow, and to change its direction.

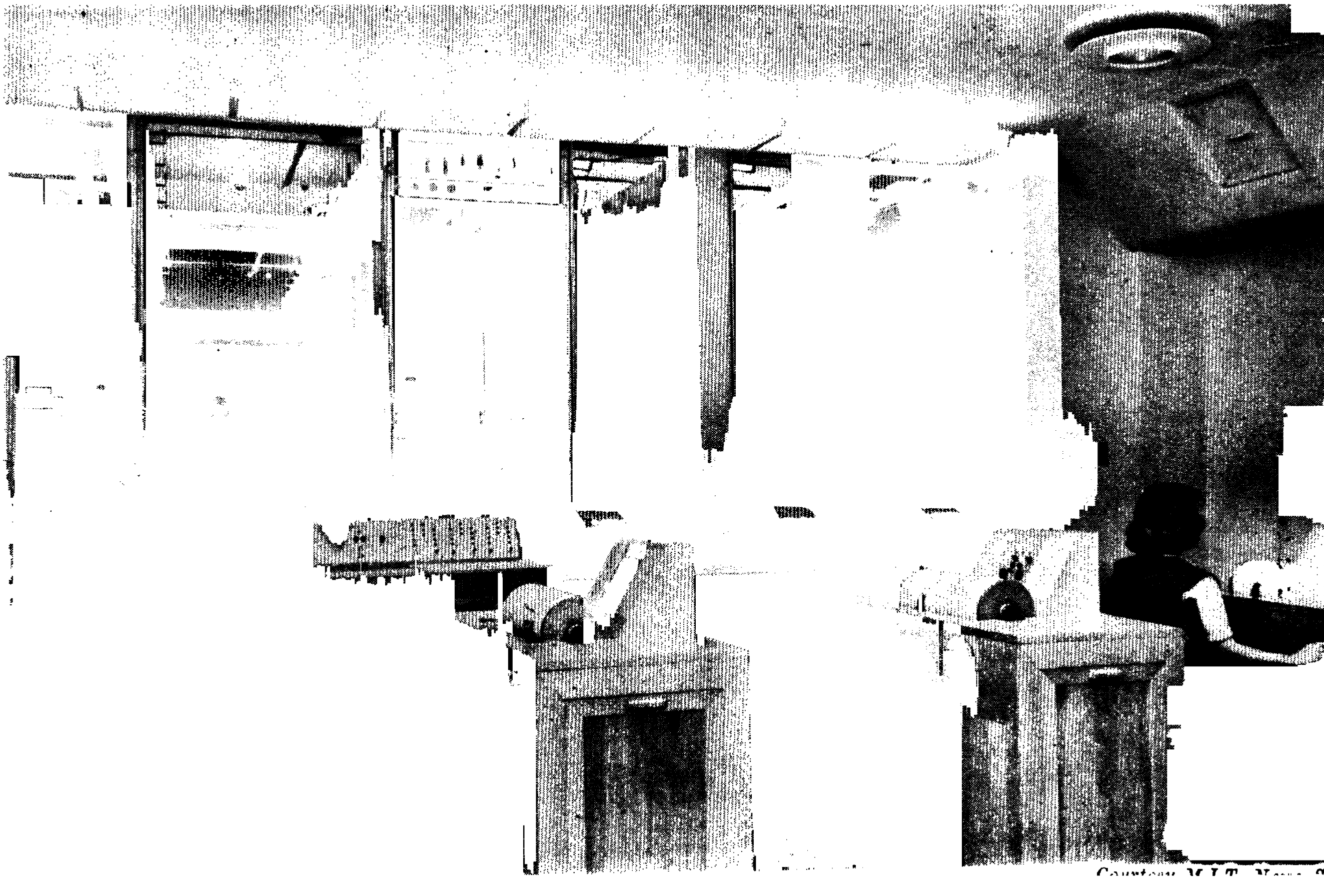
It became necessary to send a beam of light over a measured course at various directions to the assumed ether wind. The optical apparatus was mounted on a massive stone slab which floated in mercury. Light from a source on the slab was directed towards a lightly-silvered mirror near the center of the apparatus, which reflected a part and transmitted the rest. Two beams of light at right angles to each other were thus available, both derived from the same source. After traversing approximately equal distances, each beam of light was reflected back to the half-silvered mirror, where reflections and transmissions combined parts of each beam into a single beam which could be observed through an eyepiece. Since the two beams, now combined, had been derived from a single source, interference was expected and observed; the instrument is called an interferometer, and is often used in

the measurement of small distances, for the interference pattern moves when the length of either light path is varied.

A change in either light path by motion of the appropriate mirror is not the only possible cause for a shift in the observed interference pattern, or so it was believed. If the light were actually moving in an ether stream, then the relative motion of the ether stream would alter the time taken by each ray of light to complete its course, which amounts to the same thing as altering the actual length of the path. To test this point, the slab was caused to rotate slowly while an observer followed the eyepiece in order to observe the expected periodic shift in the interference pattern. Calculations based on the known motions of the earth in space had foretold exactly what the shift would be, and it was not small. But when the experiment was performed no shift was observed, though even a small fraction of the earth's motion could have been detected if the experiment were capable of detecting motion of this sort.

Discussion provoked by the negative result of the Michelson-Morley experiment was to result in the theory of relativity. It was typical of Einstein that he regarded this failure to detect motion of the ether past the earth as evidence that no such motion existed. It is also true that the world had to wait for an Einstein to hit on such a simple explanation. The ether had too firm a hold on scientific minds.

Other attempts at an explanation were made. J. J. Thomson had been engaged on researches concerning the force field around electric charges and had shown that energy is required to set a charged body in motion, with the result that the motion of the charge would be retarded in the same manner as would accompany an actual increase in mass. He was also able to show that the field around a moving charge was so distorted by the motion that the body could be treated as if it had shrunk along a direction parallel to the motion. The amount of shrinkage depended on the ratio of the speed of the charged body to the velocity of light.



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In 1893 FitzGerald made the suggestion that the negative result of the Michelson-Morley experiment could perhaps be explained by assuming that all lengths in the apparatus which were parallel to the direction of motion had decreased in a definite ratio which turned out to be the same ratio occurring in Thomson's theory. The suggestion was not a complete theory, scientifically formulated; it merely showed that if such a contraction could in any way be justified, the results of the experiment would make sense. The assumed shrinkage would be just sufficient to counteract the difference in time taken along the two light paths. FitzGerald was undoubtedly influenced by electrical ideas and there was some reason to believe that matter might be composed at least in part of charged bodies, but at this time the electron theory of matter had not become established, nor had radio-activity been discovered. The Rutherford atom did not arrive until 1911.

Two years later, in 1895, Lorentz formulated an electron theory in which matter was supposed to consist of electrical charges combined in some way through the interaction of electric and magnetic forces. If these forces existed in the ether, then motion through the medium would distort the forces and hence change the size and shape of the body which was moving, since the relative positions of the charged components would change with the forces. According to this theory, motion through the medium would produce exactly the shrinkage suggested by FitzGerald—but only if matter were really electrical in nature; there was the rub. The important point is this: By making enough additional assumptions, the negative experimental result could be explained without disposing of the ether.

The experiment was repeated in 1905 by Morley and Miller, again with a negative result. Among similar experiments, that of Trouton and Noble, in England, searched for the expected rotation of an electrical condenser while being charged; interaction of the electrical field of the charged condenser with the ether, at first regarded as a possible source of

industrial power, turned out to be too small to observe in the laboratory. The negative result was explained on the basis of the Lorentz theory. An experiment of Trouton and Rankine sought to detect the FitzGerald contraction directly by measuring the electrical resistance of a wire, first when parallel to the assumed motion and then when at right angles to it. A change in length of the wire would result in decreased electrical resistance, but again no effect of any sort was found. Rayleigh and Brace performed an optical experiment to see if the properties of a transparent doubly-refracting crystal might show changes resulting from shrinkage along one of its axes, but none were found. Miller has recently repeated the initial experiment and has reported a small effect of a positive nature, which indicates a motion at variance with the motion of the earth as determined from the stars in our vicinity. Other repetitions of the experiment, notably one performed by Michelson just before his death, have indicated no perceptible motion.

In this way the stage had been set for Einstein: The Michelson-Morley experiment, carefully performed by men of standing in the field of experimental science, had failed to detect any motion of the earth with respect to the hypothetical all-pervasive ether medium.

Einstein made a few simple postulates, each constituting a complete break with tradition, and proceeded to learn enough mathematics to enable him to work out the implications of his postulates.

First of all he assumed that no experiment performed entirely in a single system could determine whether or not this system was in uniform motion with respect to other systems. Here was truly an acceptance of experimental fact at its face value. As a matter of fact the truth of this assumption might have been recognized earlier. By means of an experiment performed in a car which is moving with uniform velocity and without vibration, an observer can not determine whether or not the car is moving unless he opens the window and looks out.

If he excludes all light and wind from outside he will not be able to tell whether or not he is moving. The case is naturally more complicated in the case of the ether, since ether wind was supposed to pass freely through closed windows and doors, and the Michelson-Morley experiment had been expected to give a positive result for the very reason that ether wind could not be excluded from a closed system.

Einstein's first postulate is thus more inclusive than any theory based on earlier ideas. A second postulate, which physically amounts to about the same thing, stated that the measured velocity of light in free space will always be the same for all observers, whether or not they are moving and irrespective of any motion of the source with respect to the observer. So far the theory was concerned only with uniform motion, the velocity being constant in the absence of acceleration.

Mathematical reasoning based on these postulates soon showed that their implications were revolutionary. The Fitz-Gerald contraction was found to be a common property of all matter, without any assumption as to the electrical or other nature of the material. The size of material objects as measured by a particular observer depends on the relative motion of object and observer, and two observers who are in motion with respect to each other will detect a shrinkage parallel to the direction of motion; each will think the other has shrunk, but will believe that his own form remains unaltered.

The apparent increase in mass with velocity predicted for electrical bodies by Thomson and later incorporated into the Lorentz electron theory of matter, was found to be a general property of all material objects whether or not they consisted of electrical charges. According to Newton's law of motion, mass is defined as the ratio of force to the acceleration produced. Hence as bodies move faster and faster, an even increasing force is required to maintain the same acceleration.

The new theory showed that mass and energy are related and that the energy inherent in a mass at rest with respect to

the observer, which had previously been considered small at ordinary temperatures, is actually equal to the product of the mass of the body concerned and the square of the velocity of light, which is a very large number. This equivalence of mass and energy has in the development of the atomic bomb become one of the most striking aspects of modern technology.

The disappearance of the concept of absolute time was originally one of the most surprising results of the new theory. Newton had been convinced that the time scale throughout the universe must be the same as that on earth, and that a particular instant which might be called "now" applies not only to the earth but to all parts of space. Relativity concludes that "now" is a rather difficult concept, and that one should be careful in claiming that two events actually occurred at the same time. If the events occur in two systems at rest with respect to each other and fairly close together, there is not much difficulty. But if the systems are widely separated or in motion with respect to each other, simultaneity may be impossible to establish, since measuring instruments and clocks will be affected by relative motion and the behavior of these instruments will alter the interpretation of signals. Even the fundamental unit of time becomes different for the two observers, and each will believe the other's watch is falling behind. Of course, neither knows which one is really moving or in fact what the true motions are; only relative motion can be determined.

The postulates and their conclusions given above formed a part of what is called the special or restricted theory of relativity and apply only to unaccelerated motion. In 1915 Einstein published his general theory of relativity, including the effects of acceleration and force. Basic to the general theory is the recognized fact that forces resulting from acceleration, especially centrifugal forces, can not be distinguished by their effects from gravitational forces. In the general theory Einstein predicted that light would be attracted by heavy bodies and that starlight passing near the sun would be deviated

from its linear path by the sun's gravitational attraction. He also predicted a change in the time scale near heavy bodies.

During the intervening years Einstein and others have attempted to extend the theories to include all human experience. Although separate theories account for gravitational and electromagnetic forces, it has not yet become possible to combine the two satisfactorily. Neither has the quantum theory, useful in the treatment of small-scale phenomena, been combined with the others. The aim of Einstein and indeed of all scientists has been to discover a very few fundamental principles which stand the test of experiment and from which can be derived the laws of gravitation, electromagnetic action and, if possible, the quantum relations. Such an all inclusive theory should also account for the existence of the electron and the other elementary particles. If such principles could be found, it could be said that a true and complete explanation of the workings of nature had been discovered. It would seem that physical science is still a long way from the attainment of its ideal objective.

Experiments in verification of the theories of relativity have been numerous and conclusive. The shortening of objects in the direction of motion is too small to permit experimental test unless relative speeds are greater than those easily attained with any object whose length can conveniently be measured, but verification of a sort is given by the Michelson-Morley experiment. The variation of mass has been tested. In experiments performed by Kaufmann in 1901 and 1906, beta rays from radium were deflected in electric and magnetic fields. The paths of the deflected electrons were entirely as predicted on the assumption that mass increases with increasing velocity in the manner predicted. Other experiments were more conclusive, since previous theories had suggested an increase in the mass of electrical particles. Sommerfeld's contribution to the Bohr atom included the change in mass of electrons moving in elliptical orbits, but here again charged particles were concerned. A clearer case

is present in the motion of the planet Mercury. This planet, of all the members of the solar system closest to the sun, consists of the same sort of material present in the earth. Its orbit is highly elliptical, so that the planet moves faster when nearest the sun than when in other parts of the orbit. The orbit itself moves slowly around, so that the long axis of the ellipse continually changes direction with a rate considerably greater than that predicted by Newtonian mechanics. Calculations based on relativity, however, including the predicted change of mass with velocity, agree exactly with the observed change, and the motion of the perihelion of Mercury, the point of the orbit nearest the sun, is evidence in support of the theory. Orbits of the other planets are more nearly circular; the speed of the bodies is more nearly uniform and the change of mass small, with the result that the older Newtonian mechanics accounts well for their motion.

The theory has predicted an attraction of starlight which passes close to the sun. The effect can be observed only during a solar eclipse, when obscuration of sunlight allows the stars to be seen. Photographs taken during a total eclipse can later be compared with others of the same region when the sun is in a different part of the sky. The test was made for the first time in 1919 by a group of British astronomers in Africa, and by another group in South America. Tests have been repeated during more recent eclipses and the evidence is now sufficiently complete to convince the most sceptical.

The general theory of relativity also predicts a change of the time scale in the vicinity of heavy masses where gravitational forces are intense. In such a place clocks, even perfect clocks, would run more slowly than on earth. Time actually passes more slowly. If it were possible to see a person in such a region, he would appear to grow old less rapidly than on earth; at the same time he would think that persons on earth were growing old more rapidly.

To test the time scale in different places, the most convenient type of clock is an atom which is emitting light. The

frequency of the light depends on the time scale in the neighborhood of the source, and is constant under ordinary conditions. Values relating to the time scale in remote parts of the universe may be obtained by measuring the frequency or wave length of light reaching the earth from these regions and comparing this frequency with that of similar light from terrestrial sources.

From astronomical evidence it is possible to determine the size and mass of certain stars and it is known that the faint companion of Sirius, both members of a double-star system, has the tremendous density of approximately a ton to the cubic inch. In this dense star the atoms apparently have been stripped of their outer electrons by thermal, radiational and gravitational forces, so that the star consists in large part of closely packed atom cores. In 1925 Adams, director of the Mount Wilson Observatory, measured the wave lengths of lines in the spectrum of light from this star and found that the lines were displaced toward the red end of the spectrum, corresponding to a smaller frequency and a longer time for each vibration as measured by terrestrial clocks. The magnitude of the shift in frequency, and thus of retardation of the time scale near the star as compared to that near the earth, was in accord with the predictions of the general theory of relativity.

The most spectacular verification of the theory of relativity has been presented recently in the release of atomic energy. Persons who remained sceptical when told that the sun is losing tons of heat every second and at the same time decreasing in mass by the same amount, are more easily convinced by the cataclysmic alteration of matter into energy which characterizes the operation of the atomic bomb. It would appear that the future of humanity and of civilization depends to a large extent on how the nations of the earth decide to use and apply the relation given originally by Einstein: $E = mc^2$.

Chapter 14

MICHELSON AND THE VELOCITY OF LIGHT

During the early years of the present century it became apparent that along with the electronic charge and the quantum constant of Planck, the velocity of light in free space would probably become one of the few really fundamental and universal constants of physical science. Light of all colors, heat radiation, radio waves, as well as x-rays and gamma-radiation are all forms of electromagnetic radiation and travel through empty space with the same velocity. A quantity equal to this velocity occurs in the theory of electricity and magnetism as a ratio of fundamental units. In relativity, the velocity of light is the upper limit to the velocity attainable by any material body, and the upper limit to the velocity with which any sort of signal may be transmitted. If an object could actually attain this velocity, its mass would become infinite.

In order to be able to make the above statements, experiments have been necessary, especially on the velocity of light itself. In a lifetime devoted to the study of light, including its velocity, Michelson determined to measure this quantity with such accuracy that it would not have to be measured again for many years to come. It is probable that the world will have to wait some considerable time before anyone will have the necessary skill and perseverance to improve on Michelson's work. His value for the velocity is still regarded as the value with which related measurements must be compared. If for

example measurements of the ratio of electromagnetic units or the velocity of radio waves in space agree with Michelson's value, no further questions regarding equality are asked.

Albert A. Michelson stands preeminent among American physicists. No man in any field has worked longer or more conscientiously for the attainment of his ideal. No scientist has ever left his lifework in more complete form. No physicist has ever made more exact measurements, or shown more skill in the design and manipulation of scientific apparatus. No man has been a greater inspiration to younger men. He was the first American recipient of the Nobel Prize in physics, and for a number of years the only other physicists to receive this award in America have been associates or students of his. Those who have known him best have been loudest in his praise.

Michelson was born in 1852 in Strelno, Germany, but spent most of his life in America, where he became naturalized and received his education. He was a student at the United States Naval Academy and later a member of its faculty. After short appointments at the Case School of Applied Science in Cleveland, and at Clark University in Worcester; and after a few years spent in study abroad, he was called to the University of Chicago as head of the department of physics. Even after his nominal retirement he was still the leading spirit in physics at Chicago, and continued his researches as well as some teaching. He was an excellent tennis player and something of an artist as well. When he died in May, 1931, at the age of seventy-eight, he had completed his final experiment on the velocity of light.

The experimental achievements of Michelson have been numerous. Exact measurement of the velocity of light was essentially his lifetime occupation, extending from his researches as a young student at the Naval Academy to the final measurements made just before his death. He invented the interferometer which in its many forms enables the most delicate measurements, especially of small quantities, to be

made. He also devised and performed the ether-drift experiment which led to the fruitful theory of relativity.

The principle of the interferometer has been adapted to many uses and the instrument has taken many forms, most of which have been designed by Michelson himself. By its use a change in the dimensions of an object by a fraction of the length of a light wave may be measured with accuracy; the bending of a short length of heavy steel rail fastened securely to the wall at one end, caused by the weight of a hen roosting on the other end can be made visible and measured. One form of interferometer attached to the 100-inch telescope on Mount Wilson has been used by Michelson in measuring the diameter of the larger stars. He also performed the most accurate measurement of length ever made, that of the world's standard meter bar in terms of the wave length of cadmium light, giving to the world a replaceable and indestructible standard of length in terms of red light from the cadmium atom.

In the latter experiment a form of interferometer was used. The standard meter which has been preserved in France is a bar of platinum irridium having a fine scratch near each end. When the bar is at the temperature of melting ice, the distance between the two scratches is defined by law as one meter; the yard is defined as a specified fraction of the meter. Although carefully preserved, it is possible that the bar might sometime meet with an accident; if its length could be preserved in terms of light waves, a duplicate could be made even though the bar should disappear. In his measurement Michelson chose to use light of a particular wave length in the red portion of the cadmium spectrum, since the corresponding spectrum line is sharp and ideal for use with the interferometer. He paced off the length of the bar in steps, moving an interferometer mirror out along the bar and counting interference fringes in the field of view, the number of fringes passing a reference point being related in a simple manner to the increase in light path as the mirror is advanced along the bar.

Although counting a large number of interference fringes is a very tedious occupation, Michelson succeeded in finding how many wave lengths, if laid end to end, would just reach between the defining scratches on the standard meter bar. If now the bar should be lost or defaced, one has only to set up a source of cadmium light, step off the required number of wave lengths of the red light used by Michelson, make two scratches, and the standard meter will have been duplicated. Now that other wave lengths have been measured in comparison with standards derived from the meter bar, even if the standard bar and also the world's entire supply of cadmium should disappear together, this unlikely event would not deprive the world of its standard of length.

In the design and use of the stellar interferometer Michelson had the cooperation of the Mount Wilson astronomers, especially Anderson and Pease. Even the 100-inch telescope is not large enough to produce a disc image of a star. The planets are sufficiently near for magnified images to be produced, but the stars are so far away that stellar images always appear as points of light even in the largest telescopes. Michelson conceived the idea of increasing the effective size of a telescope by mounting mirrors on a long transverse beam attached to the top of the telescope tube. Starlight reflected inward by these mirrors was reflected again into the telescope itself. In effect the aperture of the telescope was thus increased from one hundred inches to fifty feet or more, a size which would about suffice to produce a measurable stellar image. The observation in this case was an indirect one: Although a magnified image of the star was not utilized, an interference pattern produced by the two beams of reflected light gave information regarding the diameter of the stellar source. The measured diameter of the giant star Betelgeuse, situated in the constellation Orion and many times larger than the sun, was found to be in agreement with earlier estimates resulting from evidence of an astronomical and less direct nature.

The first recorded attempt to measure the velocity of light was made by Galileo and it is not surprising that the attempt resulted in failure.

Galileo tried to measure the time taken by lamplight to traverse a comparatively short distance. He would uncover a lighted lantern; when a friend on an adjacent hill saw the lantern he was to uncover another, so that Galileo could, he hoped, measure the elapsed time between the uncovering of his own lamp and the return of light from the remote station. It did not take him long to realize that the great speed of light would hardly permit measurement of the time of transit over such a short distance, especially with a technique of such crudity. Somewhat later Römer was able to obtain an estimate of the velocity of light by observing eclipses of satellites of the planet Jupiter at different times of the year; he determined the approximate time required for light to cross the earth's orbit, and although the actual diameter of the orbit was not known with modern accuracy the resulting value for the velocity was fairly good.

Reference has been made in an earlier chapter to the experiment of Foucault, whose measurement of the velocity of light in air and liquids provided support for the wave theory. His technique was modified from that of another French scientist, Fizeau, who had allowed a beam of light to pass the edge of a rotating cogwheel. Light travelled from the source through the space between adjacent cogs and to a distant mirror, whence it was reflected back along its original path. The returning beam might strike a cog, in which case it would not be seen from behind the wheel; or it might pass through a space and be seen. The result depends on the speed of rotation of the wheel, the velocity of light, the distance from wheel to mirror and, of course, the spacing of the cogs. With the wheel at rest, reflected light may be observed through a space between cogs, but as the speed of the wheel is increased this light disappears and later reappears as light passes through the space next beyond that through which it passed on the

way out. At higher speeds reflected light returns through the second adjacent space, and so on. By measuring the quantities just mentioned, Fizeau obtained a value for the velocity of light.

Foucault modified the experiment and replaced the cog-wheel with a rotating mirror, thereby improving the accuracy. In this experiment light from the source was reflected from the rotating mirror to a distant fixed mirror, back to the moving mirror and into a telescope with crosshairs. In the time taken by the light to make a round trip between the mirrors, the rotating mirror will move through a small angle so that the telescope must be moved to a new position in order to observe the returning light. The speed of light was calculated from measurements on the motion of the telescope, the speed of the mirror, and the length of the light path.

Michelson's method was an improvement on that of Foucault. When first performed by the young faculty member at the Naval Academy, equipment was improvised from apparatus designed for use in classroom instruction. Joseph Henry in his experiments on electromagnetism had also been forced to rely on makeshift apparatus borrowed from lecture equipment. Even with such meager apparatus Michelson at the age of twenty-six obtained a more accurate result than had previously been found.

In numerous repetitions, Michelson continually improved his experimental accuracy. One essential requirement is a high speed of rotation for the mirror. He devised a special steel mirror of octagonal cross section, whose faces were accurately ground to eliminate distortion of the reflected rays. With eight faces instead of one or two, more reflections became possible during each rotation of the mirror and the intensity of light finally entering the telescope was correspondingly increased. The mirror was rotated by an air turbine at a speed which was determined by comparison with a vibrating tuning fork. It is also desirable to have as long a base line as possible, with a correspondingly long interval

during which the mirror can rotate while the light travels out and back. Since this time for the round trip is very small at best, the accuracy of the result increases as the time becomes longer. Finally, the length of the base line between mirrors must be known to the same accuracy as other quantities involved in the experiment.

After several laboratory experiments, Michelson decided to do the job in a big way. For the site of his observing station he chose Mount Wilson, six thousand feet above sea level in a region of comparatively stable climatic conditions, where the established observatory could provide equipment and necessary services. The distant mirror was placed more than twenty miles to the eastward on the slopes of Mt. San Antonio, known locally as Old Baldy. An extremely accurate determination of the horizontal distance separating the two end points was provided by the U.S. Coast and Geodetic Survey.

These experiments were performed in the years immediately following 1924. Light from a powerful electric arc was accurately focussed and made to fall on the surface of the octagonal mirror, which was rotating at high speed. Thence it was again focussed and started out in a parallel beam toward the distant mirror on Old Baldy. Here it was reflected to a small concave mirror used to improve the focus, back to the large mirror and then across the intervening space to the original station on Mount Wilson. Here it was refocussed on the revolving mirror and into the telescope used for observation. The displacement of the returning light, with respect to the reference direction obtained with the octagonal mirror held stationary, was measured by means of crosshairs in the field of view, controlled by a fine micrometer adjustment.

The result of this experiment was a figure for the velocity of light which was accurate to one mile per second, a high accuracy indeed when one remembers that the velocity is approximately 186,000 miles per second. But Michelson was troubled by even so tiny an error, and proceeded to lay plans for what was to be his last experiment.

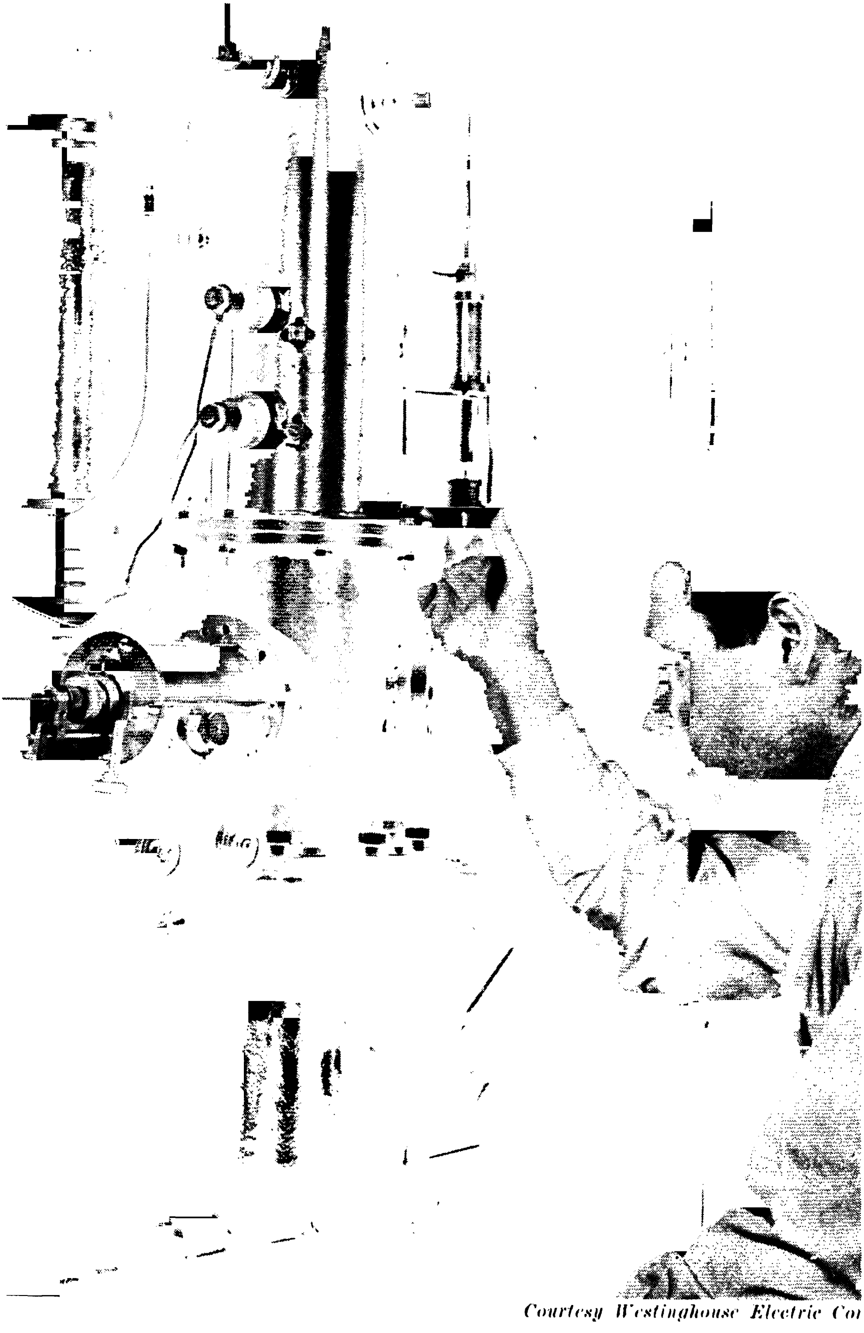
In spite of the steady atmospheric conditions near Mount Wilson, the image of the returning beam was often blurred by heat waves in the intervening air. Michelson desired to perform the experiment in a vacuum, not an easy task in view of the size of chamber required. Accordingly a pipeline one mile long and about a foot in diameter was laid down on the ground at a ranch near Santa Ana, California, not far from Mount Wilson. The pipe was nearly evacuated by large pumps; a perfect vacuum would have been impossible in so long a pipe. The rotating mirror and associated equipment was set up at one end of the pipe. By repeated reflection the light was made to travel not once but ten times the length of the pipe in each direction, with a resulting effective light path comparable to that in the earlier experiments. But now atmospheric disturbances had been eliminated. At this point Michelson collapsed from overwork; from his bed he continued to direct the work, now presided over by his associate, Dr. Pease of the Mount Wilson Observatory staff. Before he died he knew of the successful conclusion of the experiment and dictated a part of the final report.

Chapter 15

THE ELECTRON

THE RECENT ADVANCES in physical science which have been outlined in earlier chapters emphasize the important role played by the electron in science and in nature. All matter contains electrons. The analysis of optical spectra, as well as an understanding of electrical conduction through solids, liquids or gases depends on knowledge of the properties of electrons, as does the theory of the conduction of heat through solid bodies. Without familiarity with this fundamental particle, the disintegration families of radioactive products would still be mysterious. Developments in the design of modern x-ray tubes, as well as triumphs in electronics resulting from use of the modern vacuum tube would not have become possible without knowledge of the charge and mass of the electron as well as its behavior under all sorts of conditions.

The natural unit of electricity was anticipated in Faraday's work on electrolysis and ionization; Maxwell was perplexed by the apparent atomicity of electricity, but Stoney went so far as to give a name to the hypothetical unit even though it was not certain whether such a unit really existed in nature. In the work of Thomson, Rutherford, and their colleagues it became possible to study particles which gave every appearance of possessing the very charge implied by Faraday's results and anticipated by Stoney. The ratio of charge to mass of these particles had been determined, and individual estimates of charge and mass had been made. Various means were found



Courtesy Westinghouse Electric Co.

for producing streams of electrons; they could be produced as cathode rays in a discharge tube or by the action of x-rays or ultraviolet light on metals. Similar particles were emitted by radioactive substances, and could be obtained from hot metal filaments.

Since particles having the same charge could be produced in so many ways, it was strongly indicated that the electronic charge might really be a fundamental unit. Although various measurements of the charge were not exact, agreement was fair. Particles produced in the above ways always had the same ratio of charge to mass and the unit charge appeared to be that presumed by Stoney. But the mass seemed to be much smaller than that of the hydrogen atom or ion, the smallest mass then known to exist. Indecision concerning the mass furnished some doubts as to the charge.

The final proof that the electron is a fundamental unit, indivisible and having a definite and constant quantity of charge, was to be given in experiments performed by the American physicist Robert A. Millikan.

For his work on the electron, as well as experiments establishing Einstein's photoelectric equation on a firm foundation, Millikan has been awarded the Nobel Prize in physics. He has attributed much of his success to earlier association with Michelson in Chicago. Until recently he was director of the physics laboratory at the California Institute of Technology in Pasadena, where his inspiration has led younger men to achievement in many lines of physical investigation. He has lately been occupied with a study of cosmic radiation, penetrating radiation from beyond the earth, which furnishes guidance in the interpretation of natural laws and may supply evidence of happenings in remote regions of space.

It has been stated that electrolysis enables calculation of the elementary charge. It is easy to determine the amount of charge required to separate a given quantity of hydrogen or other substance from an electrolyte; division of this quantity by the number of atoms liberated gives a quantity of charge

which presumably is the elementary charge if, as is the case with hydrogen, the ion happens to be univalent and thus singly charged. A difficulty with this method lies in the uncertainty as to the number of atoms or molecules present in a given volume of gas.

Rutherford and Geiger had been able to measure the double charge on the alpha particle by noting the total charge of collected particles and counting them through scintillations. In his experiments on specific charge, the ratio of charge to mass, J. J. Thomson was concerned with similar questions and was at home in the field of electrical conduction in gases.

It had been discovered that air molecules are ionized or torn apart by x-rays and gamma radiation, and that conduction through gases depends on the presence of charged ions, a situation very similar to that obtaining in electrolytic conduction. Thomson was able to estimate the size of the assumed unit charge by measurements on gaseous ions. But instead of noting the amount of charge necessary to collect a given quantity of ionized gas, a method useful with liquids but attended with grave difficulties in the case of gases, he found certain relations between the total charge on all ions in a cubic centimeter of gas, and the constants of diffusion and mobility of the ions, quantities which are subject to experimental measurement. Here again the number of atoms, molecules, or ions in a cubic centimeter was not known with great accuracy and as a result the individual charge was not exactly determined. Estimates from various sources of the size of the fundamental unit of charge were in fair agreement, not sufficiently good however to warrant an assertion that the electronic charge is always the same, and indivisible: in fact, a fundamental unit.

Direct measurement of the electronic charge was necessary and a new series of experiments was indicated. The earliest type of investigation, forerunner of later experiments, is illustrated by an experiment performed in England by Townsend in the year 1897. Hydrogen and oxygen obtained by the electrolysis of an acid solution have been found to contain numer-

ous ions. By forcing the gas through water and allowing it to rise into a container, a cloud is formed, consisting of water vapor which has condensed on the ions that remain. Townsend used this technique and measured the total electrical charge on the cloud by means of an electrometer connected to the collecting chamber. The average size of the water droplets in the cloud was found by allowing the cloud to settle slowly under the action of gravity; a theoretical relation given by Stokes provides information on the rate of fall of various-sized spheres through air, and by this law the droplet size could be calculated from the observed rate of settling. The total weight of the water cloud was determined by drawing the air and vapor in the container through a tube containing a drying agent, so that the difference in weight of this tube before and after collecting the vapor furnishes information on the weight of water in the cloud. From the size of each droplet, on the average, and the total weight of the cloud Townsend computed the weight of each droplet, again an average value, and from this and the total weight he obtained the number of droplets in the entire cloud. He thus knew the number of droplets as well as the total charge, and it became a simple matter to calculate the average charge on each droplet.

The method of Townsend represented a real advance in that the method was new and it was no longer necessary to know the number of molecules contained in a cubic centimeter of the gas. But the method was open to objections, since the droplets might be of many different sizes, and some might have multiple charges while others remain completely uncharged. Besides, Stokes' law of fall was based on theoretical considerations and had not been adequately tested. The method was nevertheless to undergo a number of revisions until finally in the hands of Millikan the answer was to be given.

The experimental arrangement was modified by Thomson. Instead of obtaining ionized gas by electrolysis, he caused moist air to become ionized by exposure to x-rays. The total

charge on the ion cloud was determined by measuring the conductivity of the cloud. Thomson arranged two metal plates in the chamber, connected a battery and galvanometer to the plates, and observed the amount of electric current passing through the region of ionized gas between the plates. In the absence of ionization no current will flow through such an arrangement, but in the presence of ions the current is proportional to the amount of ionization in the gas, since current through the gas is actually the motion of charged ions. The weight of the cloud was found from a theoretical consideration of the rate of cooling of the gas on sudden expansion. In other respects the experiment resembled that of Townsend and the result was not much different.

In 1903 H. A. Wilson, working in Thomson's laboratory, made radical changes in the technique and was able to obtain a still more accurate value of the elementary charge. Two metal plates were arranged in a horizontal position in an enclosed chamber, one above the other. Air between the plates was ionized by x-radiation. By means of auxiliary apparatus, air in the chamber could be rapidly expanded. When this was done, the gas was suddenly cooled and moisture condensed around the ions. If left alone, the resulting cloud would settle under the action of gravity. But if a battery were connected to the plates so that electric forces acted on the charged cloud, the rate of fall could be increased or decreased at will. It was still necessary to make use of Stokes' law to determine the average size of droplet. Then by noting the rate of fall of the cloud, first in the absence of any electric field and again in the presence of the field, it was possible to compute the average charge on the droplets.

It was now to be Millikan's turn. In 1908 he reported an experiment similar to that of Wilson, with comparable accuracy. In an attempt to improve the accuracy he applied a higher voltage to the plates, reducing still further the rate of fall in the presence of an electric field. If a large difference in the rates of fall in the presence or absence of the field could

be obtained, it would be possible to reduce the time required for readings and thus decrease the possibility of error from evaporation of the cloud. Success came in a manner which was hardly anticipated: desiring a field strong enough to hold the cloud stationary and prevent its settling, still higher voltages were applied to the plates. But when the field was applied the cloud simply disappeared: ions had been sucked out of the space by electrical attraction to the charged plates.

But was the cloud completely gone, might not a few droplets with exactly the correct ratio of charge to weight have remained balanced in the space? On searching for such droplets Millikan found one or two, appearing as small brilliant points of light under the strong illumination supplied.

Millikan recognized at once the importance of what had happened. The observation of single droplets, which could be kept under observation for a considerable time and be made to rise and fall repeatedly in the field of view, enabled far greater accuracy than did observation of a whole cloud of droplets. The only difficulty was that the drop evaporated, the change in mass resulting in a changed rate of fall. Millikan sought a liquid which does not evaporate and found watch oil to be completely satisfactory.

In the latest form of the apparatus, accurately spaced metal plates of large diameter are used to produce a very uniform field of electric force. The system is enclosed in a larger chamber surrounded by an oil bath to maintain constant temperature and thus avoid disturbance of the droplet by convection currents in the air. A fine mist of oil is sprayed into the chamber above the plates and one or two droplets find their way through a small hole in the upper plate and enter the experimental region between the plates, in the field of view of the microscope used for observation. The droplet can then be kept under observation for as long a time as is desired. The drop is charged by collection of ions from the surrounding air after the latter has been exposed for a short time to gamma radiation from a sample of radioactive material, and

the charge may be changed in the same manner if a different charge is desired on the same droplet.

In a long series of measurements extending to 1917 and including the use of many droplets and numerous measurements on each drop, Millikan produced the most conclusive evidence for the fundamental nature of the electronic charge as a natural unit of electricity. The upward speed of the drop in the presence of the electric field can be changed by altering the charge on the drop, and it was found that the amount of charge computed for each separately observed rate of rise, using a single droplet in a field of constant strength, was always exactly some integral multiple, never a fractional part, of the fundamental charge. The result was the same whether the sign of charge on the drop was positive or negative.

If very tiny droplets were used, comparable in size to an air molecule, corrections to the law of Stokes became necessary. Millikan's data enabled these corrections to be made, providing not only final proof of the atomic nature of electric charge but also a corrected law for the falling of very small bodies through air.

It is important to know that the electron is the fundamental unit of electric charge, but it is just as important to know exactly the value of this charge. For years the experimental value obtained by Millikan has been standard. Recently slight revisions have been made on the basis of all experiments in which the electronic charge enters. Knowledge of the magnitude of the electronic charge has enabled calculation of the number of molecules in a cubic centimeter of air, a result often desired but previously difficult to determine. Since the product of this number and the electronic charge had been known, it was now possible to obtain the number. From the ratio of charge to mass of the electron, accurate determination of the charge has given also the magnitude of the mass.

A few investigators have brought forward what they regard as evidence for the existence of a charge smaller than that of the electron, evidence which is generally regarded as incon-

clusive. If the electronic charge is ever to be subdivided it is probable that other than electrical means will be required. The chemical atom was never divided by the methods of chemistry, other methods being required to break it up into its component parts: electrons, protons, and neutrons. The same thing is undoubtedly true of the electron. If ever a smaller unit of charge is to be found, new methods will be necessary. At present the electronic charge, Planck's constant, and the velocity of light in empty space, are regarded as the most fundamental and universal constants of physical science and of nature.

Chapter 16

PHOTONS

THE QUANTUM THEORY, the modern corpuscular theory of radiation, has very little similarity to the corpuscular theory of Isaac Newton, who could not have suspected a majority of the facts upon which the modern theory has been based. It may be that a corpuscular theory of light is a more natural one than a wave theory, since it does not require the assumption of an elastic medium to support the propagation of waves. Evidence for the truth of the wave theory was however so overwhelming in the absence of facts unknown before the year 1900 that the earlier corpuscular theory was unable to survive. Recent researches have finally succeeded in combining parts of both theories into a consistent whole, a theory of matter and radiation which is probably destined to last for some time to come.

The invention by Planck of the quantum of action, as well as the discovery that the radiation process is discontinuous, initiated development of the new theory. After Einstein in his theory of the photoelectric effect had injected the idea of the light quantum, and Bohr had incorporated quantum concepts into the theory of spectroscopy and atomic structure, the wave theory was in a considerably weakened position, still further undermined by the photoelectric experiments of Millikan. It was generally recognized that emission and absorption of radiant energy occurred in discrete units, or quanta, of the size predicted. But many physicists still found it diffi-

cult to accept the idea that light is actually transmitted from place to place in the form of corpuscles rather than spreading wave fronts. It appeared impossible to explain the facts of interference and diffraction on the basis of any corpuscular theory. These effects are now explainable, and have been observed, in the case of streams of material particles: electrons, even atoms, sometimes behave as if associated with some sort of wave motion. Before 1925 however the quantum theory and the wave theory existed side by side, each more or less independent of the other. One theory was called upon to explain what the other could not.

Einstein's theory of the photoelectric effect was published in 1905, but it was not until 1916 that Millikan had completed his experiments in this field and had produced strong evidence in favor of Einstein's assumption of the light quantum, the packet of radiant energy which is now called the photon.

It will be recalled that the velocity of photoelectrons depends on the color or wave length of incident radiation, while the number emitted depends on the intensity. Einstein predicted that the absorption of a single photon, whose energy is the product of the frequency (reciprocal wave length multiplied by the velocity of light) and Planck's constant, would produce one photoelectron which would be emitted with a kinetic energy equal to the energy of the photon except for the energy required to extricate the electron from the metal.

It was generally recognized that an exact experimental verification of Einstein's equation would be convincing evidence for the existence of the postulated light quantum, the photon which replaces the wave train of the older theory.

Millikan chose to work with the alkali metals, sodium and potassium. Since photoelectrons are ejected from these metals by visible light as well as ultraviolet radiation, an especially wide range of wave lengths could be used. Many metals are not affected by visible light except in the extreme violet region. A threshold in the red region would thus per-

mit greater experimental variation with a resulting increase in accuracy.

The equation to be tested includes a term denoting the work done in pulling the electron out of the metal surface. For this reason particularly it was necessary to obtain standard surface conditions. The alkali metals are chemically very active and oxidize with great rapidity in air. The apparatus had to be enclosed in an evacuated chamber, not only to avoid contamination of the metal but also to allow free motion of the photoelectrons.

The final form of the apparatus used by Millikan has been compared to a miniature machine shop inside a glass vessel which could be evacuated. The metal samples were mounted in small cups placed on the circumference of a wheel which could be rotated by means of a magnet held outside the tube. Inside was placed a little boring machine, also operated by manipulation of external magnets, to enable scraping and cleaning of the metal surface after air had been pumped from the tube and before observations were made. The tube also contained an assortment of electrical apparatus for the control and detection of photoelectrons.

Imagine that the tube has been evacuated and that everything is ready for performance of the experiment. After selecting the particular metallic specimen to be investigated, the wheel is rotated so as to bring this specimen opposite the boring tool. This tool is then brought up against the metal and given a turn or two, scraping off the oxide film and leaving a clean metal surface. The tool is then retracted and the wheel given another small rotation to bring the sample in proper position relative to the electrical apparatus.

Light of known frequency and wave length is admitted and allowed to fall upon the metal surface, with the result that photoelectrons are produced. The equipment is so arranged that these electrons cross part of the evacuated region and fall upon a metal gauze, connected to an electrometer to enable the counting of collected electrons. A battery is con-

nected between wheel and collecting gauze in such a direction as to retard the electrons, and the velocity of electrons is measured by increasing the voltage and thus the retarding electric field until no electron can reach the collector. It is known both from theory and experiment what velocity is acquired by an electron that is accelerated by a potential difference of, say, a hundred volts; conversely, an electron with this initial speed would just be stopped by an opposing potential difference of the same amount. Thus for each frequency of incident light the speed of the resulting photoelectrons can be measured by increasing the retarding field until the electrometer shows that no electrons are reaching the collector.

The results obtained by Millikan in these experiments on photoelectricity turned out to be in complete accord with the predictions of Einstein as expressed in his famous equation. The results were plotted graphically, with the frequency of incident light as one argument and the kinetic energy of the electrons, or the value of retarding potential required to stop the electrons, as the other argument. A simple relation between any particular retarding potential and the kinetic energy lost by an electron subject to this potential, made either quantity useful in plotting the graph.

The final form of the graph depicting Millikan's experimental results turned out to be a straight line whose slope indicated the value of Planck's constant. The line crossed the axis of kinetic energy at a point indicating the amount of work required to extricate the electron from the metal. Actually the slope was expressed in terms of the ratio of Planck's constant to the electronic charge, the latter being known through earlier experiments of the same investigator. Measurement of the slope thus led to an accurate determination of the value of h, Planck's elementary quantum of action.

Exact numerical verification of Einstein's photoelectric equation was considered to provide excellent support of the concept underlying the equation and supporting theory, that

of the light quantum, modern form of the light corpuscle. If any doubts remained they were to be removed by a series of experiments initiated by Arthur H. Compton of Chicago, performed by him and others, and reported in final form in 1922. For discovery and proof of the validity of the Compton effect, as it was called, its author received the Nobel physics award; he was the third American to achieve this recognition and the second of Michelson's younger associates to be so honored.

In Millikan's photoelectric experiments the light quantum was studied during absorption only. Complete acceptance of the new corpuscular theory demanded a study of the photon while in motion and this was provided by Compton.

The Compton effect involves the scattering of x-rays when they strike paraffin or some other suitable substance. Compton assumed that a beam of x-rays is really a stream of corpuscles or particles whose energy as given by quantum conditions can be calculated from an equation similar to the photoelectric equation of Einstein. The mass of each particle or photon may be computed by use of Einstein's equation resulting from the special theory of relativity, relating mass and energy. It was supposed that an x-ray photon might be scattered on impact with electrons in the paraffin, and that in each encounter a single photon would be involved with a single electron.

Compton was thus dealing with the impact of particles, in which the ordinary laws of conservation of energy and momentum might be expected to prevail. In fact, the type of encounter considered was quite comparable to the impact between two billiard balls, one moving and one initially at rest. In such an impact the moving ball (the x-ray photon) is deflected into a new path and the stationary ball (the electron) is set in motion. As a result of the encounter the moving ball loses energy.

In an equation based on the above assumptions, deflection angles were predicted, as were relations between angle, energy loss, and the direction in which the electron would rebound.

Since the energy of the deflected photon is equal to the product of Planck's constant and the frequency, the decrease in energy appears as a lowered frequency, which corresponds to a longer wave length. Although several experimenters were at first misled because of certain peculiarities in their apparatus, it was soon universally agreed that Compton's equation was valid. The increase in wave length of scattered x-rays, the angles through which they were deflected, and the directions of electron rebound, all fitted exactly into the equation. Final acceptance of the light quantum or photon concept, introduced by Einstein in 1905, could no longer be delayed. Although the phenomena of interference and diffraction still remained outside the fold, it was felt that the light corpuscle, wave packet, photon, or light quantum was here to stay. And at the same time the luminiferous ether died a belated and unlamented death.

More recently a somewhat similar phenomenon has been discovered by the Indian scientist C. V. Raman, involving the scattering of visible light by liquids and other material. Here again, energy is lost by the scattered photon, which emerges with less energy and a correspondingly longer wave length than it originally possessed. In this case however the amount of absorbed energy depends on the ability of particular molecules to absorb radiant energy. Either an entire quantum of energy, an entire photon, must be absorbed or there will be no interaction. Studies of the Raman effect will in many cases give as much information about the molecular structure of the scattering substance as would direct spectroscopic investigation by older methods, and the scattering process is often easier to study. Most molecular spectra occur in the invisible infrared region, whereas the Raman effect allows the use of wave lengths in the visible portion of the spectrum.

Acceptance of the photon did not immediately kill the wave theory, though it naturally put this theory in a defensive position. This situation was to remain for a few years, until discovery of electron waves and electron diffraction indicated a

way out of the dilemma. Today the quantum theory is supreme; but it is a modified theory, in which the wavelike aspects of photons and electrons, as well as atoms, accompany the concept of the light particle or photon whose mass, energy and momentum often allow it to be treated as a material particle. In geometrical optics, the wave aspects of radiation are still useful, while in other fields the corpuscular interpretation is demanded; both, however, are particular derivations from a more general and inclusive theoretical background.

Chapter 17

ELECTRON WAVES

THE PROGRESS of natural science has often been conditioned and stimulated by a belief in the essential simplicity and unity of nature. Such views were strongly held by Faraday. If he had lived today, and had seen the overwhelming evidence in favor of the corpuscular theory of the light quantum, he would have been among the first to ask the question whether particles of matter might not exhibit some of the properties possessed by a train of waves. He would have searched for evidence to complete the duality: If waves can behave like particles, why can not particles behave like waves?

The question was actually presented in 1924 by the French physicist De Broglie. His immediate concern, not exactly the duality just mentioned, arose from the Bohr theory of atomic structure. An electron in the Bohr atom was supposed to remain in an orbit of definite size for a considerable time without radiating energy or falling inward toward the nucleus. The orbits available to the electron were rigorously selected by quantum rules from the many orbits allowed on the basis of classical mechanics. De Broglie wished to find satisfactory explanations for these restrictions of the quantum theory.

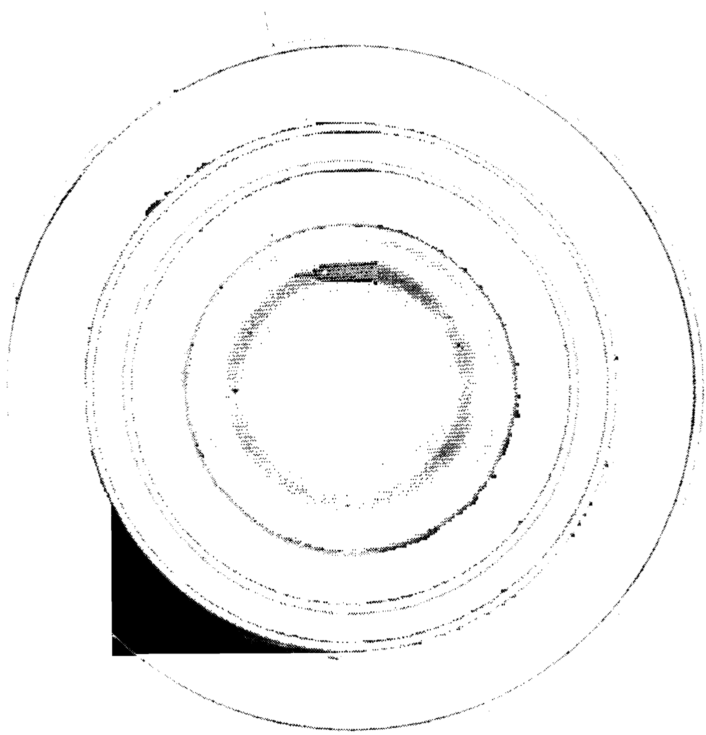
In his theoretical investigation De Broglie made use of an analogy. When a stretched string such as a violin string is set in vibration, it can be made to vibrate in one, two or more equal segments, depending on how it is bowed and where the player's finger is held. If bowed in the middle, it will vibrate as a whole, with the point of maximum vibration at the center

and a node at each end. With the formation of a single loop whose length is that of the string, the sound produced will be the fundamental tone. If the string is stopped at its center by the application of pressure from the player's finger and gently bowed at some intermediate point, the string will vibrate in two equal segments or loops to give the first overtone.

The simple vibrations of stretched strings are characteristic of standing waves, which are produced by the interference of oppositely-directed travelling waves in such a way that the positions of nodes and loops remain fixed as the string vibrates. De Broglie wondered if something related to standing waves might not be concerned in the orbital motion of electrons. Accordingly he assumed some sort of standing wave to be associated with each electron moving in a Bohr orbit, spread out around the orbit in much the same manner as the standing wave is spread out along the length of a violin string. The length of his assumed wave was determined by the condition that the circumference of the orbit should contain a whole number of loops or vibrating segments. Such an assumption would provide a stable condition, with the electron remaining in an orbit of constant size as long as the vibration should last, neither losing energy nor being forced to spiral in toward the nucleus.

The assumption was fruitful; not only did it remove the difficulty concerning stable orbits, but also it gave the correct orbit sizes. The orbital electron was limited to those particular modes of vibration which were in resonance with motion in the orbit. Thus Bohr's postulates, for which no explanation had previously been given, had in a way been explained. The existence of the assumed electron waves had not, however, been demonstrated by direct experiment.

In 1927 the electron waves predicted by De Broglie came to light experimentally and rather accidentally. The American physicists Davisson and Germer had been investigating the reflection of electrons from a nickel target. In their apparatus electrons obtained from a hot metal filament were



Courtesy RCA

Electron diffraction pattern obtained from a thin gold film.

accelerated by a potential difference applied between the source and a metal plate in front provided with an opening. The electron beam thus obtained was further defined and focussed by means of apertures and electric fields. The narrow beam was directed upon the polished face of a nickel crystal which could be moved into different positions, the reflected electrons being collected in a metal chamber connected to an electrometer. The entire assemblage was enclosed in a highly evacuated glass container. Information was sought which would be of use in the design of x-ray and industrial vacuum tubes, and which might also be of great scientific value.

The crystal and collecting chamber were moved into various relative positions in order to make a complete study of electron reflection from the different faces of the sample and to obtain information on the numbers of electrons reflected at various angles. At first the results followed accepted theories; from the position of greatest reflected intensity, the number of reflected electrons decreased continuously with increase in angle. Emphasis should be placed upon the word 'continuously.'

As frequently happens, an experimental accident was to result in a new discovery. In this case the accident was the breaking of the tube. After a new tube had been made and the air pumped out, it was necessary to heat the nickel target in order to drive off attached gas molecules which otherwise would come off slowly and prevent the attainment of a sufficiently good vacuum. During the heating, something happened to the crystal structure of the nickel, for when the experiment was repeated the reflected electrons no longer behaved as before. Instead of decreasing continuously from the angular position of maximum reflections the reflected intensity decreased suddenly on each side of the maximum, only to increase again at larger angles. Instead of a smooth curve relating the reflected intensity to angle of reflection, the curve was jagged and showed a number of humps. There appeared

to be several preferential directions in which more electrons were reflected than in other positions.

This unexpected result called to mind the experiments of the Braggs on x-ray diffraction, in which x-ray wave lengths were measured and crystal structure studied by the interference pattern produced by x-rays scattered from the individual atoms in a crystal. In this case a number of isolated spots on a photographic plate indicated the directions of maximum intensity in the diffraction pattern. A curve of intensity vs. angle would have shown humps corresponding to these positions.

The positions of maxima as observed for scattered electrons in the experiment of Davisson and Germer were somewhat similar to those observed in experiments on x-ray diffraction. Calculation of the equivalent wave length for the electrons in the reflected beams, on the assumption that a sort of diffraction phenomenon was present and that for this case at least the electron could be considered to have an equivalent wave length, soon showed that this assumed wave length associated with the reflected electrons was very close to values predicted by De Broglie. This wave length was equal to the ratio of Planck's constant, the quantum of action, to the momentum of the electron which is the product of its mass and velocity. It looked as though some sort of wave were involved, although it was not known what kind of wave it was or, indeed, just what was vibrating.

At about the same time the apparent wave length of moving electrons was appearing in a different way. In Aberdeen, Scotland, G. P. Thomson had been observing the effect of passing positively-charged atoms through thin metal foils. He noticed that after these particles had traversed the foils and been registered on a photographic plate behind the foil, the central image on the plate was often surrounded by concentric rings. Something very similar is observed when x-rays are diffracted by powdered crystalline material, and also when visible light is diffracted by passage through a tiny opening.

At the time however Thomson did not ascribe the rings to a diffraction effect; instead of thinking in terms of electron waves he preferred to consider the rings as produced in a manner similar to that which results in the well known optical halo effects. But when Thomson and Reid repeated the experiment with electrons and still observed the same effects, and when they discovered that use of the De Broglie wave length for the electrons led to the prediction of diffraction rings in exactly the observed positions, they hastened to attach the wave explanation to the phenomena. Since then Thomson has done considerable work of a similar nature and has always obtained results consistent with the explanation. Rupp in Germany has performed equivalent experiments, and Kicuchi in Japan has investigated the diffraction of electrons by mica, obtaining results in complete accord with the wave interpretation. The wave lengths are still the same as those first discussed by De Broglie.

If moving electrons really have an equivalent wave length, it should be possible to diffract a beam of electrons by use of an optical diffraction grating, especially if the beam strikes the grating at glancing incidence. It had recently been found that even the short x-ray waves would undergo diffraction by a grating under these conditions, with the incident rays almost parallel to the surface so that the space between lines on the grating is effectively decreased. The wave length of slow electrons is in the region of x-ray wave lengths. Rupp tried the experiment in 1929 with the greatest success, the amount of diffraction being exactly as expected on the basis of the De Broglie wave length.

It thus appears that some sort of wave must be associated with moving electrons, which had ever since their discovery been considered to be material particles. The same may be said for moving atoms. Attempts at a satisfactory explanation of this surprising feature of matter in the form of particles were not long delayed. It will appear shortly that some of these attempts have met with success.

Chapter 18

WAVE MECHANICS

THE DISCOVERY of electron waves, coming soon after the final proof that radiation is corpuscular in nature, clearly demanded the formulation of a new theory of radiation and matter. This theory, which is concerned with the motion of photons, electrons and the other fundamental particles of nature, and especially with the interaction of matter and radiation, has been given the name, quantum mechanics, or wave mechanics. Methods have been developed from the powerful mathematical techniques of generalized dynamics and mechanics which were evolved during the earlier classical period of physical science, but the theory is packed to the brim with the very latest discoveries and concepts, with often a daring conjecture or two. The new theory combines valid aspects of the wave theory of light, the quantum theory of radiation, and the dynamics of particles in motion.

As very often happens, the new theory had its origin not so much in a remarkable discovery as in a change in emphasis, a shift in point of view.

In 1925, before the wave nature of the electron had been discovered but after De Broglie had presented his theory of material waves, it had become clear that something was wrong with the Bohr theory of atomic structure. For a number of years the concept of electronic orbits had been found useful in the explanation and analysis of optical and x-ray spectra, but it was becoming more and more certain that the picture

was not complete. Spectrum lines were observed which could not be made to correspond with any known electronic orbit and special orbits had to be provided, often with very little reason other than that the spectrum seemed to demand them. As the accuracy of spectrum analysis was improved and the fine structure of spectrum lines was studied in greater detail it soon became necessary to discard the actual picturing of electronic orbits and to concentrate on energy levels for electrons in the atom. Energy levels had played an important role in the Bohr theory, but it had been believed that a close correspondence existed between energy levels and actual electronic orbits. The model of the atom was being more and more frequently disregarded because of its increasing inability to account clearly and definitely for the facts of experimental spectroscopy.

The new theory, most recent form of the quantum theory, has developed along a number of lines. Wave mechanics has been an extension of the mathematical treatment of classical wave theory, while quantum mechanics has made use of more generalized methods. Both methods have been fruitful. Included in the theory are the quantum postulates of Einstein and Bohr relating to the discontinuous nature of absorption, emission, and propagation of light and other forms of radiation, as well as the concept of the localized energy of the photon. Guiding principles have been derived from the mathematical treatment of dynamics as worked out years ago by Hamilton and others for the solution of problems in celestial mechanics. A fundamental principle throughout has been the idea first emphasized strongly by Einstein and later specifically by Heisenberg, that it is meaningless for science to talk about things unless it can get its experimental hands on them. For example, electronic orbits in the atom can not be observed directly. They may or may not exist; probably they do in a sense, but it is a waste of time to base a theory on them. Rather, one should concentrate attention on things which are

directly observable: spectrum lines, wave lengths, frequencies, the energy of an ejected electron or other particle.

It soon appeared that a previously unrealized and fundamental uncertainty exists in nature. Ever since the dawn of science it had been believed that experimental accuracy could be improved indefinitely, and that the only limit to this accuracy was the gross nature of measuring instruments. But apparently a definite limit to experimental accuracy is fundamental in nature. It used to be the custom to imagine ideal experiments having infinite accuracy and discuss the results which would be obtained if such experiments could be performed. Such a view was justified only so long as real or imagined measurements were confined to regions where the fundamental indeterminacy of nature was not involved, the gross region of ordinary human experience. But in the realm of very small dimensions, of interaction between particles of atomic size, the older ideas of infinite accuracy have been forced to give ground.

The unavoidable inaccuracy of certain observations has been summed up in the principle of uncertainty as formulated by Werner Heisenberg. Imagine that an electron is moving rapidly through some sort of apparatus in the laboratory. As it passes a particular point the observer wishes to determine its position and velocity. The electron is too small to disturb the long wave lengths of visible light and, if observed at all, must be illuminated with the very short waves of gamma radiation. But a gamma-ray photon has a great deal of energy, much more than that of a photon of visible light, because its frequency is so much greater. The gamma-ray photon must strike the electron in order to reveal the electron's presence. But when it does, the large energy and mass of the photon is too much for the feeble electron, which may be knocked completely out of the apparatus. The operation of observing the electron has so altered its velocity that it is impossible to gain any idea as to what velocity the electron really had.

One can look at a house without doing damage but the same

can not be said of the electron. In the world of very small dimensions the observation is not independent of the observer.

It appears that one can measure either the position of an electron or its velocity, but not both at the same time if great accuracy is desired. Radiation of short wave length will determine the position of the electron, but interaction between photon and electron prevents measurement of its velocity. If longer wave lengths are used, position becomes indefinite because the electron is so small in comparison to the light wave.

According to the uncertainty principle, or the principle of indeterminacy, Heisenberg has shown that the experimental uncertainty in position, when multiplied by the simultaneous uncertainty in velocity, both in magnitude and direction, is of the order of magnitude of the quantum constant given by Planck. The result seems plausible when it is remembered that the fundamental uncertainty in experimental accuracy depends on the interaction of observer and observed, and that the interaction must occur in units of energy involving h, the quantum of action.

It has been stated that not only light, but as well electrons and atoms, exhibit diffraction phenomena when properly treated. In the case of light, Huygens' principle and the interference of waves provide adequate explanation. When a light wave meets a screen provided with a very small hole, the opening acts like a new source of spherical wavelets so that the original beam of light becomes a bundle of divergent rays and light bends around corners. The smaller the hole, the more is the resulting divergence.

Suppose that instead of light a stream of electrons is incident on the screen. At the opening each electron must obey Heisenberg's principle of uncertainty. If an electron gets through the hole at all, its position is accurately defined at the instant of passage; but at the same time its velocity becomes correspondingly indeterminate and it can go forward in any direction it likes. The result bears a close similarity

to the optical prediction of Huygens: a narrow parallel beam of electrons is changed by passage through the opening into a widely divergent beam. The particles move forward in all directions and the methods of statistics must be used in an analysis of their behavior.

One branch of the new theory has been the wave mechanics of Schrödinger in which a wave equation derived from classical mechanics is modified to include recent discoveries. Developments by Heisenberg and others have followed somewhat different lines and have made considerable use of a branch of mathematics involving the array of numbers and symbols which is called a matrix. A theoretical development of Dirac has included relativity and the assumed inherent spinning motion of the electron, introduced by Uhlenbeck and Goudsmit into the theory of spectra to account for the fine-structure of spectrum lines. All these theories are highly mathematical, though based entirely on observable entities.

According to the modern point of view, electrons are observable statistically but not individually, when simultaneous determination of position and velocity is desired. Instead of referring to the position of an electron in an atom, one now speaks of the probability that an electron may occupy a specified region. In place of electronic orbits one considers the probable density of charge at definite points, corresponding to the relative time spent by a moving electron in various positions. The inner orbits of the Bohr atom have become a smear of charge, the density of the smear being determined by probability considerations. Farther from the nucleus, where the electron moves more slowly, its position becomes more definite and the electron becomes more localized; under these conditions the correspondence principle of Bohr, relating quantum and classical conditions in the outer orbits, takes on new meaning. If an electron is ejected from the atom in the process of ionization it becomes the localized particle of the older theory, unless it is moving too rapidly.

The new theory has been immensely successful, not only in

Courtesy R

Diffraction pattern of bauxite crystals.

accounting correctly for facts explained by older theories; it also will account for observations unexplainable by the older theories and has led to predictions which later have been verified experimentally. It has been especially useful in the analysis of spectra and in the interpretation of electron diffraction. Equations occur whose solutions correspond to definite energy values, comparable to the energy terms of the Bohr theory. The quantum numbers of spectroscopy and atomic structure are thus inherent in the theory and are given in fundamental terms, not as the result of arbitrary assumptions. These numbers, and indeed the very discreteness of physical and atomic processes, appear as a natural result of the new theory.

Quantum mechanics has solved the problems for which it was designed, problems concerned with the atom but not at first with the atomic nucleus, which was considered to be a particle of definite charge and mass. Application of the theory in attempts to gain further understanding of the radioactive process, which clearly involves the nucleus, has not only resulted in expansion of the theory; some understanding of the nucleus itself has been attained, including its structure and energy relations. Knowledge in this field is far from complete and new experiments involving higher and higher energies are in preparation. But enough knowledge has already been gained to enable the effective release of at least a small part of the tremendous store of energy residing in the inner core of the atom.

Chapter 19

THE ATOMIC NUCLEUS

A VERY FEW years ago the term modern physics was understood to mean electron physics. At present the term applies unequivocally to the field of nuclear physics.

After the invention or discovery of the nuclear model of the atom, more than two decades passed before much was known about the nucleus itself. The charge and mass of the nuclei of various atoms were determined, and speculation had arisen concerning the possibility that all nuclei might consist of a few elementary components including perhaps the proton, nucleus of the hydrogen atom. The nucleus was known to contribute in some manner to the spontaneous disintegration of the radioactive elements, though what its role was, and whether all the particles and radiations emitted by these substances originated in the nucleus itself were still open questions.

Evidence obtained by Rutherford in 1919 strengthened the view that the nucleus was in fact a composite particle. The production of high-speed protons by alpha particles plowing through the atoms of gaseous nitrogen, first evidence of artificially-induced transmutation, showed clearly that either the nitrogen nucleus or the alpha particle, probably the former, since the alpha particle was regarded as very stable, had undergone a drastic alteration. If particles could be knocked out of the nucleus, it was fair to assume that these particles had originally existed in the nucleus. The thought that the

particles might have been instantaneously brought into existence by the mutual action of alpha particle and atomic nucleus seemed too absurd to warrant consideration.

High-speed electrons are ejected by radioactive atoms in the form of beta radiation. This fact seemed to indicate that electrons as well as protons might participate in the nuclear constitution, and for a considerable period it was generally supposed that nuclei were composed of electrons and protons. The hydrogen nucleus was a simple proton, the helium nucleus a combination of four protons and two electrons to produce the required mass of approximately four units on the atomic scale with a net positive charge of two units. The fact that the mass of the alpha particle or helium nucleus was less than four times the mass of the hydrogen nucleus was explained on the supposition that the difference in mass had been metamorphosed into energy, in this case the binding energy of the composite particle, which was known to be very stable. Calculation of binding energies, or mass defects, by use of Einstein's relation between mass and energy showed that various nuclei possessed unequal stabilities, and verified the unusually high stability of the helium nucleus.

It is now believed that electrons as such are not present in the atomic nucleus. After a short period during which references to nuclear electrons were accompanied by strong warnings as to the serious difficulties involved, the discovery of a new particle provided an escape from the dilemma.

In an experiment performed in Germany in 1930, Bothe and Becker bombarded a number of light metallic elements with alpha particles. As a result of this bombardment they observed radiation of great penetrating power, greater even than that of the very penetrating gamma radiation. Two years later Irene Curie, daughter of Marie Curie, and her husband Joliot repeated the experiment in Paris. The penetrating radiation was allowed to fall upon a block of paraffin, with the result that protons of very high speed were produced. These and similar experiments strengthened the belief that

the new radiation was not the same as gamma radiation; the final argument was however given less than a year later in England by Chadwick, who showed that the radiation was in reality a stream of uncharged particles, each having a mass not far from that of the proton.

1932 was a fruitful year for the discovery of new fundamental particles. Besides the neutron, both the positron and deuteron appeared for the first time. The positive electron was discovered in cosmic-ray experiments performed by Anderson in Pasadena, while knowledge of the deuteron, nucleus of the heavy hydrogen or deuterium atom, resulted from the discovery by Urey and his associates at Columbia University of heavy hydrogen and heavy water.

It is now believed that atomic nuclei consist exclusively of protons and neutrons. Again, the hydrogen nucleus is the proton, but the helium nucleus contains two protons and two neutrons to give a mass of four units with a charge of two units.

The extreme penetrating power of a stream of neutrons, which in fact led to their discovery, depends on the fact that these particles are uncharged. They are able to pass close to a large number of atoms, even nuclei, without suffering deflection, because they are not subject to electric forces. A direct hit will result in deflection, but the particles are very small, as are the nuclei of atoms, and a direct hit is not very probable. If the neutron is moving among heavy atoms, collisions will be nearly elastic and the neutron continues on its way through unbelievably thick samples of the material; but if it is moving through hydrogen or some substance such as water or paraffin which contains a large number of hydrogen atoms, it will lose a considerable portion of its energy and momentum at every impact with another particle of approximately equal mass. This fact makes water an excellent shield for the protection of persons engaged in neutron research. A few substances exhibit selective absorption of neutrons within a

particular range of velocities, and are practically opaque to such neutrons.

Atomic nuclei, then, consist of protons and neutrons in various combinations. Stable nuclei of light elements contain nearly equal numbers of each, but heavier nuclei have more neutrons than protons. The heaviest nuclei of all, those of the radioactive elements, are not stable at all. Neither are a number of lighter nuclei after an extra neutron or proton has been forced into the nucleus by laboratory bombardment; such nuclei are said to be artificially radioactive.

But what holds the nucleus together, generally in a stable condition? The positively-charged protons must repel each other. But scattering experiments as well as theoretical considerations have shown the existence of a very special kind of force, which only extends a short distance but which within this range is very powerful, a force of attraction between particles. Doubtless a great deal more will soon be known about the nature of this force, for the problem is being earnestly attacked. It has been determined, however, what particular combinations of protons and neutrons will result in a stable configuration. The neutron and proton are both regarded as fundamental and stable particles, though there is some reason to believe that within a nucleus a proton can change into a neutron and a positron, or a neutron change into a proton and an electron of the ordinary negative sort.

The concept of binding energy mentioned above applies as before, though the nucleus in now believed to consist of protons and neutrons rather than protons and electrons. In this connection an experiment performed in England by Cockcroft and Walton in 1932 is instructive. As a matter of fact this experiment initiated the entire series of artificial transmutations, of which so many are known, and of which a number have resulted in the artificial production of radioactivity.

Cockcroft and Walton arranged apparatus to produce a beam of high-speed protons by accelerating positive hydrogen ions from a gas discharge; the ions were drawn into an

accelerating tube maintained at low pressure, and acquired speeds corresponding to the applied potential difference of 700,000 volts. In the path of the proton beam was placed a sample of lithium metal, which was thus bombarded by the protons.

It was soon observed that alpha particles were emitted from the lithium target under the energetic bombardment. The only possible conclusion was that lithium atoms had undergone transmutation into atoms of helium. It would be more correct to say that nuclei had been transmuted, since the nucleus is principally responsible for the chemical nature of an atom, and in the experiment hydrogen nuclei were used as projectiles. After impact, however, the nuclei would soon pick up electrons and become stable atoms.

The experiment is interpreted on the basis that the combination of a proton whose atomic number is one and whose atomic weight is one unit (on a scale based on the proton), with a lithium nucleus of atomic number three and atomic weight seven on the same scale as above, produces two helium nuclei or alpha particles, each having an atomic number of two and atomic weight approximately four. Symbolically:

$$_3Li^7 + {}_1H^1 \rightarrow {}_2He^4 + {}_2He^4.$$

To complete the relation it must be recalled that the incident protons have considerable kinetic energy, as do the resulting alpha particles. Also, the mass of a helium atom is a little less than the mass of the combined atoms of hydrogen and lithium. When these energies are included, and converted into equivalent mass units by use of Einstein's equation relating mass and energy (or the mass units in the above equation similarly converted into energy units, which amounts to the same thing) the equation balances, with the same numerical quantity occurring on each side. Thus transmutation has been demonstrated, and Einstein's equation justified.

The efficiency of this particular process is not high, and the net result of the experiment is a loss in energy. No interac-

tion occurs unless a direct hit is suffered by a lithium nucleus, and then only if conditions of energy and momentum are suitable. More energy must be put into the apparatus than is obtained from a performance of the experiment.

Experiments of the same sort have resulted in the laboratory transmutation of nearly all the elements. Results obtained have been extremely useful in furnishing information on atomic and nuclear structure, and radioactive products of certain transmutations have been of use in the practice of medicine, principally in the treatment of cancer and in the research or clinical application of the method of tracer elements. Experiments described in recent issues of the daily press depend on oral feeding of radioactive iodine compounds with the hope that they will be selectively absorbed by particular organs, in this case the thyroid gland, and produce more conveniently the same result as the external application of radioactive compounds. Progress of the experiment can easily be followed, since the temporary radioactivity of the iodine atoms makes their presence in very small numbers readily detectible.

One important result of laboratory experiments on transmutation has been an understanding of the process of energy production in the sun and other stars of the same type. The carbon cycle proposed by Bethe has since been included in theories of stellar evolution, and has been found to predict physical conditions similar to those actually observed. The process derives energy from the combination of hydrogen into the more stable element helium. Carbon plays a role similar to that of a chemical catalyst, in that it enters into the reaction and helps it go to completion, but in the end is unchanged by the process. In laboratory experiments, particles are accelerated by the application of high voltage, or may be obtained from radioactive elements, natural or artificial. Temperatures in the interior of the sun and other stars, possibly twenty million degrees, are so high that the thermal

energy of atoms and ions is sufficient to produce effective impacts. Such reactions are called thermonuclear reactions.

The first step occurs when a high-speed proton strikes a carbon nucleus in an effective manner:

$$_6C^{12} + {_1H^1} \rightarrow {_7N^{13}}.$$

The same terminology is used as above in discussion of the Cockcroft-Walton experiment. The nitrogen nucleus here obtained is unstable, artificially radioactive and thus different from the ordinary isotope of nitrogen, and soon undergoes a change, the result of which is:

$$_7N^{13} \rightarrow {_6C^{13}} + {_1e^0}.$$

The symbol e in this case represents a positron or positive electron whose charge is of course unity and whose mass is nearly zero on the atomic scale. An isotope of carbon is produced, which may suffer an impact with a proton:

$$_6C^{13} + {_1H^1} \rightarrow {_7N^{14}}.$$

This nitrogen isotope again suffers an impact:

$$_7N^{14} + {_1H^1} \rightarrow {_8O^{15}}.$$

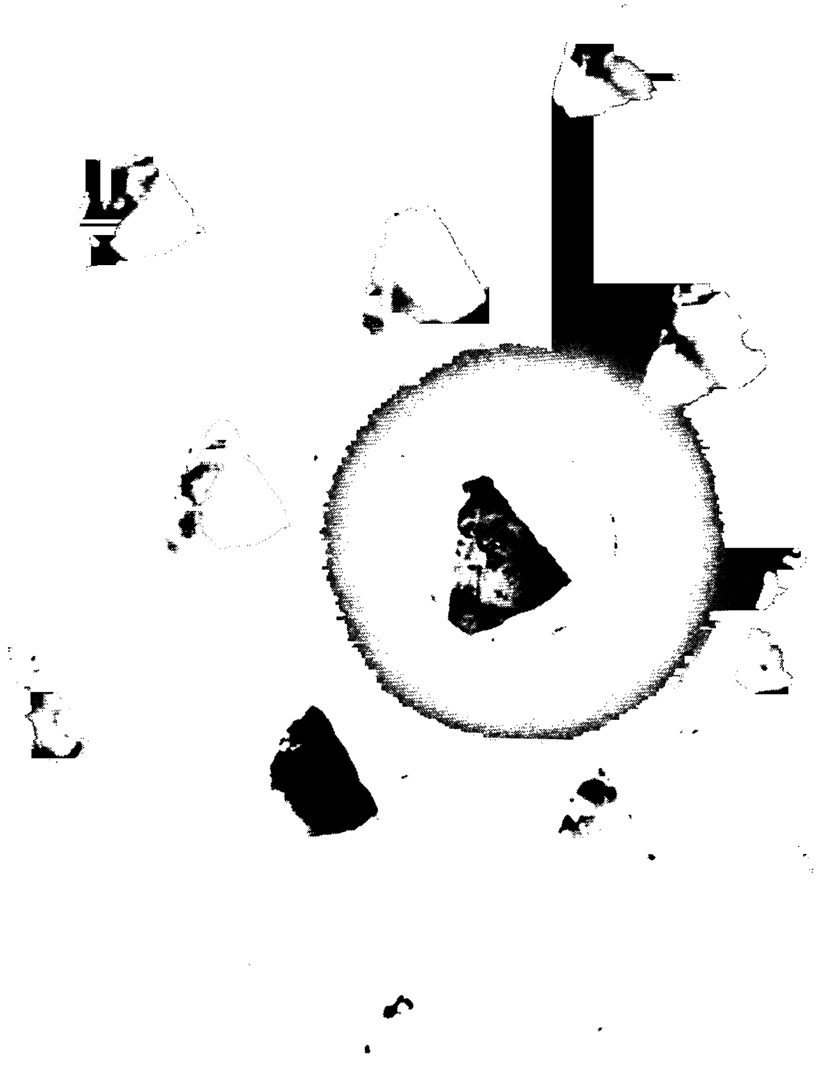
The oxygen isotope formed by this action is radioactive and soon emits a positron according to the relation:

$$_8O^{15} \rightarrow {_7N^{15}} + {_1e^0}.$$

Finally, impact of a proton with the new nitrogen nucleus completes the cycle:

$$_7N^{15} + {_1H^1} \rightarrow {_6C^{12}} + {_2He^4}.$$

The normal carbon atom or nucleus is regained, hydrogen has been changed into helium, and energy has been liberated. The amount of energy obtained is the energy equivalent of the difference in mass between the helium atom and four hydrogen atoms, and appears in the emission of positrons, which soon are altered into the form of radiant energy, as well as



Courtesy RCA

gamma radiation produced during the operation of the cycle. The above transmutations have been observed experimentally, and the cycle accounts for the correct rate of energy production in the sun.

In the field of nuclear physics, the concept of the energy-well has proved useful. Particles can get out of a nucleus if they can scale the sides of the analogous well. The roller coaster of amusement resorts provides an illustration: If the car has descended a slope and is momentarily in the valley before the next rise, its kinetic energy will cause it to ascend; whether it gets over the top of the next hill depends on the height of the hill. If the hill is too high, the potential energy of the car at the top would have to be greater than was the kinetic energy at the bottom and the car will not reach the top at all.

Particles in the nucleus have energy. Whether this energy is sufficient to cause ejection of the particle depends on how much work must be done in getting out, i.e., the fate of the particle depends on the height of the potential hill which it faces. Particles in the nucleus are thus in a manner of speaking surrounded by walls, which they can scale whenever they acquire sufficient energy. The concept has furnished explanations pertinent to the process of natural radioactivity and has been found useful in the newer field of artificial radioactivity and transmutation. Of course the shape of the potential well, including the steepness and height of its sides, depends on the nature of the nucleus. In the radioactive nucleus, energy is shared and transferred between particles until one particle happens to acquire enough energy to get out of the well. When it does, the particle is emitted from the nucleus.

Chapter 20

THE RELEASE OF ATOMIC ENERGY

A NUMBER of authors and advertising writers have at times found it convenient to make use of Einstein's mass-energy relation in a striking, though until recently quite hypothetical, illustration. If all the energy in a candle or a box of matches, a pat of butter or a teaspoonful of gasoline could be utilized, this energy would be sufficient to raise a battleship or a large building through a specified vertical distance. It is still impossible to change the entire mass of material objects into radiant energy, and fortunately so; the small fraction of the energy which has already been released appears to be sufficiently destructive.

The atomic bomb was subtly foreshadowed in 1905 when Einstein published his special or restricted theory of relativity. It did not seem at all possible, however, until 1939, when the fission of uranium atoms under neutron bombardment was discovered.

Soon after the neutron became available for use in atomic experiments it was realized that this particle might be an effective projectile, especially in studying the nuclei of heavy elements. Alpha particles have plenty of energy, but they are repelled by the electric force between themselves and the target nucleus, whereas neutrons are not subject to such forces. Accordingly Fermi in 1934 bombarded various elements with neutrons and obtained results which indicated that something was happening, though no one knew just what.

Early in 1939 Frisch and Meitner, refugees from Germany who were working in Bohr's laboratory in Denmark, were convinced that neutron bombardment of uranium produced a number of lighter components, and that in the fission of the uranium atom large amounts of energy were released. About the same time, Hahn and Strassmann in Germany published a report of their experiment in which barium had been detected among the fragments. Niels Bohr had just come to this country, and Fermi was at the time a member of the staff at Columbia. Einstein and his associate Wheeler at Princeton were excited by the news; as well as Fermi and his associates at Columbia, they knew that something big was happening in the science of physics. Fermi suggested that since heavy nuclei contain more neutrons relative to the number of protons than do the lighter elements, the fission of uranium into lighter components should leave a few neutrons left over. Experiments were immediately arranged in the laboratories at Columbia and other institutions, and in the February 15, 1939 issue of a single scientific publication four laboratories reported the successful performance of fission experiments: Columbia, The Carnegie Institution of Washington, Johns Hopkins University, and the University of California. Word soon reached Bohr that similar results had been obtained in his own laboratory by Frisch, and Joliot published observations of the same nature in a French journal. The quarry had been identified and the huntsmen were in full cry.

The significance of the new discoveries was twofold: In the first place, the uranium atom had been split into pieces with the evolution of a great deal of energy. All that was needed to accomplish this result was one uranium nucleus and a single neutron having the right amount of kinetic energy. In the second place, though the reaction was started by a single neutron, several neutrons were released in the act of fission. In a bulk sample of uranium, why could not one of these neutrons produce fission of another nucleus, and so on in cumulative fashion? It began to appear possible that a self-sustaining

chain reaction might be induced under the right conditions. But what were the right conditions?

At this point the veil of secrecy descended over all work in the field of nuclear fission. Certain aspects of the search for the right conditions, pursued for a while by scientists of the Office of Scientific Research and Development presided over by Vannevar Bush, and later by scientists and engineers in the Manhattan Engineer District project of the U.S. Army Engineering corps, have been revealed by H. D. Smyth. The official report on atomic energy for military purposes, called the Smyth report, and issued in 1945, has received wide publicity and has often been quoted.

It was generally known that if a chain reaction were to be self-sustaining, a certain minimum amount of material must be present so that enough neutrons might be captured by enough uranium atoms. But how much material was required?

After preliminary studies of the probability of collision and capture, an attempt was made to determine the minimum size of a uranium pile which would support a chain reaction. The first successful pile was prepared at Chicago by the staff of the Metallurgical laboratory using data from an earlier pile at Columbia. Material was added slowly, while neutron intensity was carefully checked with sensitive detecting instruments. Uranium of great purity was used, as well as carefully refined graphite which was inserted here and there in the pile to slow down the neutrons emitted in the fission process to a speed suitable for inducing further fission. Safety valves were present in the form of rods of material which could be manually or automatically inserted to absorb neutrons and stop the reaction if things got too hot.

As building of the pile progressed the neutron intensity increased until a point was reached at which operation of the pile was self-sustaining. Precautions in the design and construction of the pile had provided a controllable, nonexplosive source of energy, using the chain reaction of neutron-induced fission of uranium atoms. Similar piles have been constructed

at the project plants in Hanford, Washington and Oak Ridge, Tennessee.

Uranium contains isotopes 234, 235, and 238; it is the isotope of weight 235 on the atomic scale which undergoes fission, but this isotope is present in normal uranium in very small quantities. Separation became imperative and was known to be difficult. A number of physical methods were tried, since isotopes can not be separated by chemical means from one another. The principal methods used were gaseous diffusion, centrifugal separation (principle of the cream separator), and magnetic separation. The latter method is similar in principle to that of the mass spectograph: Ions of the material are deflected as the beam passes through a strong magnetic field, with the production of several beams, each containing an isotope of a single mass. Thus ions of the isotope U-235 were collected almost one by one. Large-scale processes, however, in time produced enough purified material.

It soon became apparent that uranium atoms may capture neutrons without fission. This was true of the isotope U-238, by far the most abundant uranium isotope. In the process a new atom, U-239, is formed, which decays spontaneously into another new element, neptunium (239) and an electron. In its turn neptunium decays with the production of plutonium and the emission of an electron. It was soon found that plutonium was subject to fission under neutron bombardment, as had indeed been suspected, and that in the process a number of neutrons were liberated. Plutonium is produced in a reacting uranium pile. Its advantage is that plutonium is chemically different from material which has been present in a uranium pile. Unusual precautions are necessary in the separation, in view of the intense radioactivity of the pile, and elaborate techniques involving remote control and shielding were developed in order to protect persons concerned with operation of the plant.

The scientific facts underlying the release of atomic energy

were mostly available in 1940. Successful application of these scientific facts has been an engineering development of stupendous magnitude. Never before has application followed so closely on fundamental discovery. The background of knowledge on nuclear structure has been pretty well used up; during the war, neither time nor the scientists themselves were available for work not connected with immediate objectives. It is imperative that work proceed once more in the realm of fundamental discovery, and the present plans of scientists indicate that the urgency is recognized and that they are wasting no time.

The atomic nucleus is still incompletely understood. If the source of energy resident in the nucleus is, as we sincerely hope, to be used for the benefit rather than the destruction of mankind, much more investigation, both pure and applied, will be necessary. It is a healthy sign that scientists have taken part in discussions on the eventual use of atomic energy. The problem concerns us all, and it is right that the scientists and engineers who have brought about the new era and are able through their investigations to see a little farther into the scientific future than most, should be concerned and have a voice in the disposition of this new power which they have suddenly unearthed.

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